ECH Experiments on WHAM: X1, O1, and X2

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WHAM
Wisconsin HTS Axisymmetric Mirror

Overview

- ECH systems on WHAM
  - What is WHAM?
  - Gyrotron Hardware
  - Relevant Diagnostics
- X1 Breakdown and Hot Electron Production
  - Beam Path and Mirrors
  - X1 Plasma Breakdown and HEI
  - Fluxloop observations of Hot Electrons
  - Hard X-rays and afterglow plasma
- X2 and O1 Breakdown in WHAM-R
  - WHAM-R modifications
  - X2 Plasma Breakdown
  - O1 Plasma Breakdown

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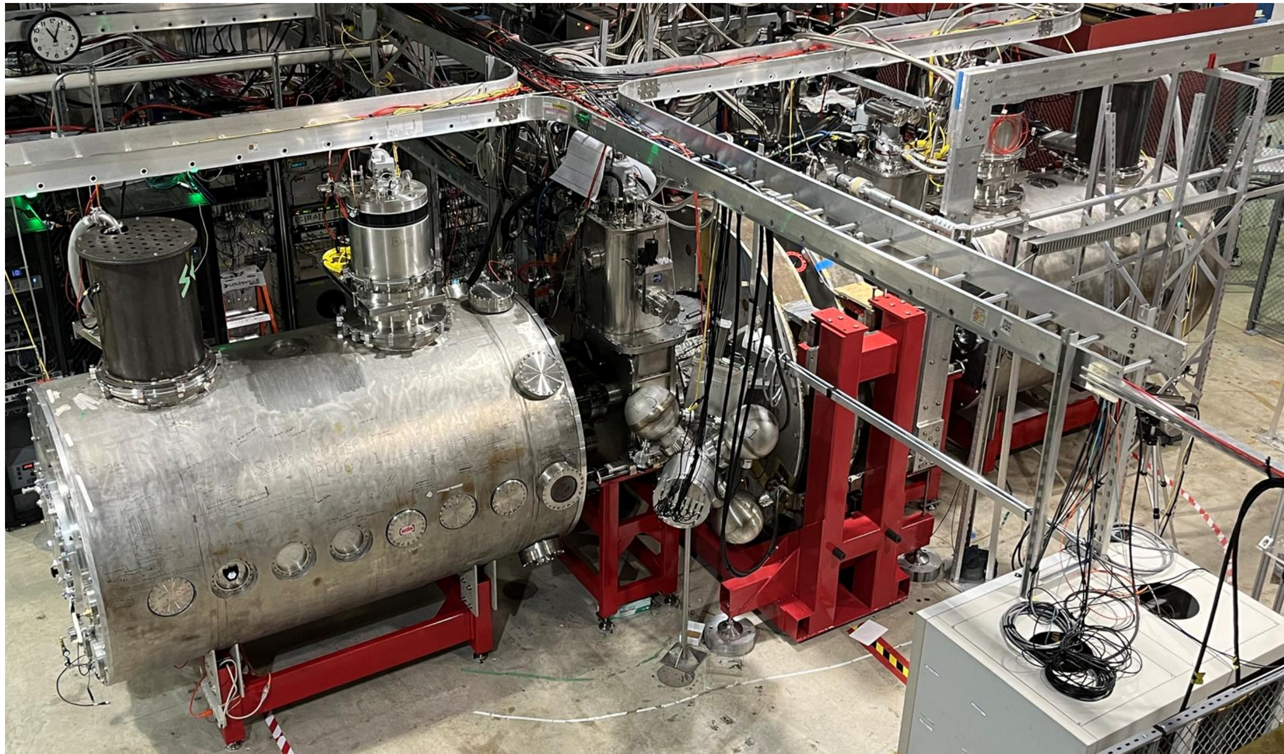
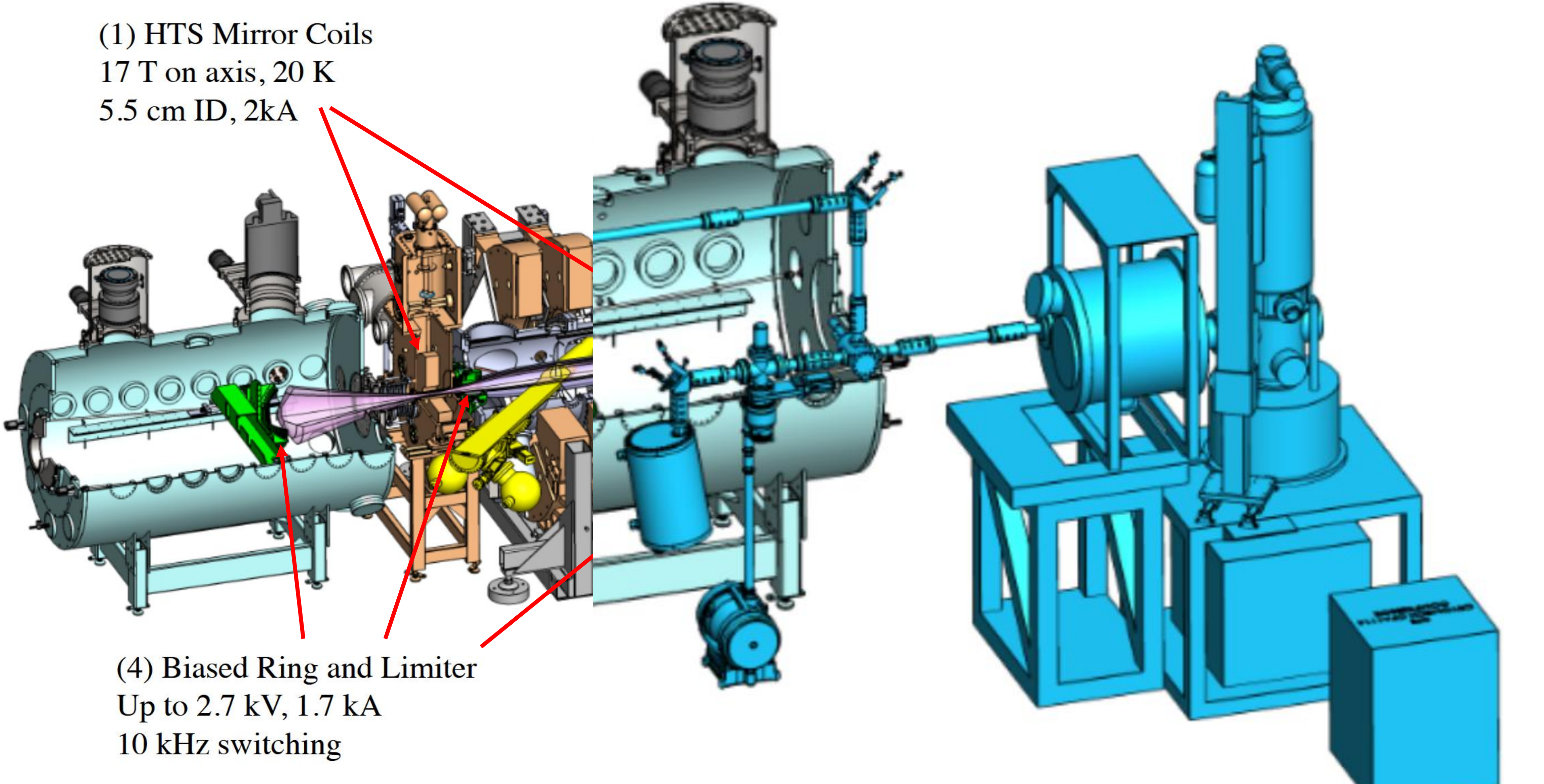
Wisconsin HTS Axisymmetric Mirror

- Simple, axisymmetric magnetic mirror
- Uses High Temperature Superconducting magnets
  - 17T, 6cm bore
  - Made by Commonwealth Fusion Systems (CFS)
- Designed as proof of concept for future devices
  - Q~1 Axisymmetric Mirror
  - Tandem Mirror reactor
- Target Parameters
  - **B_{max} ≈ 17 T**
  - **B_0 ≈ 0.25 T** - 0.8 T
  - **n_e ≈ 5E19 m^{-3}**
  - $T_e \leq 1.5$ keV
  - $\langle E_i \rangle \approx 25$ keV
- Construction started Summer 2020
- First Plasma July 2024

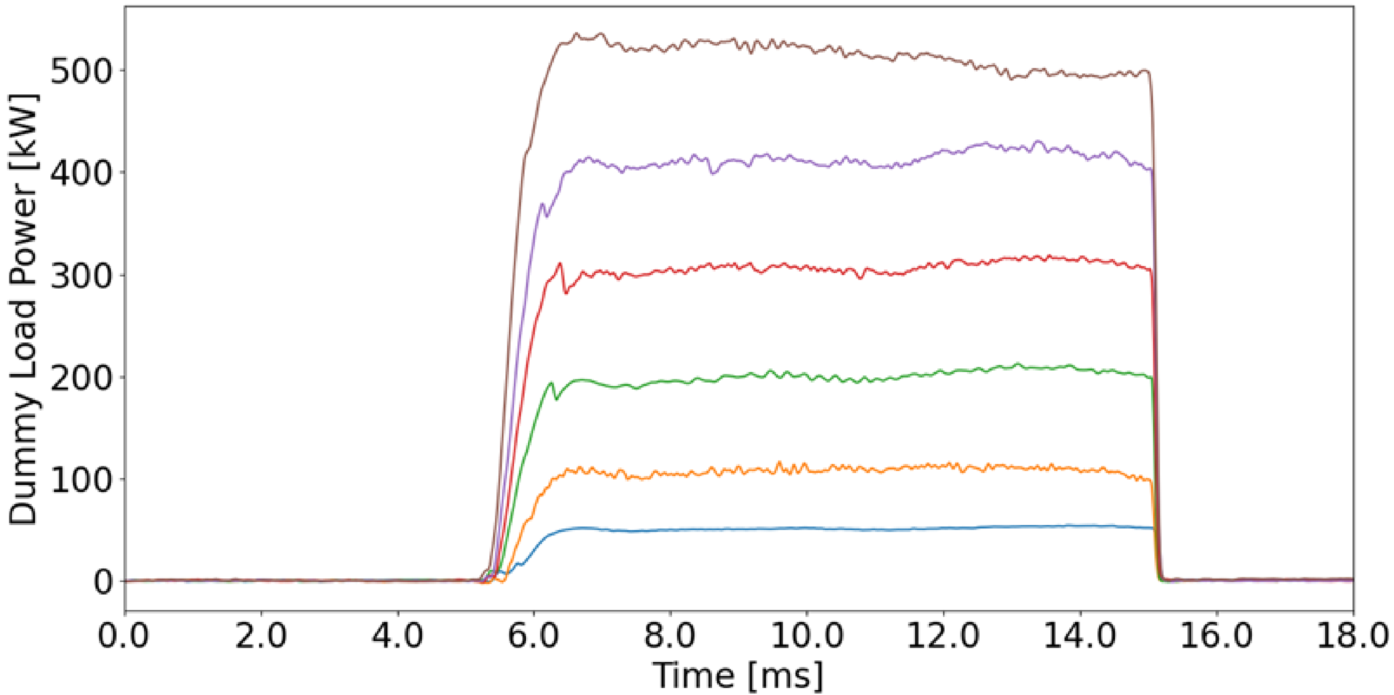


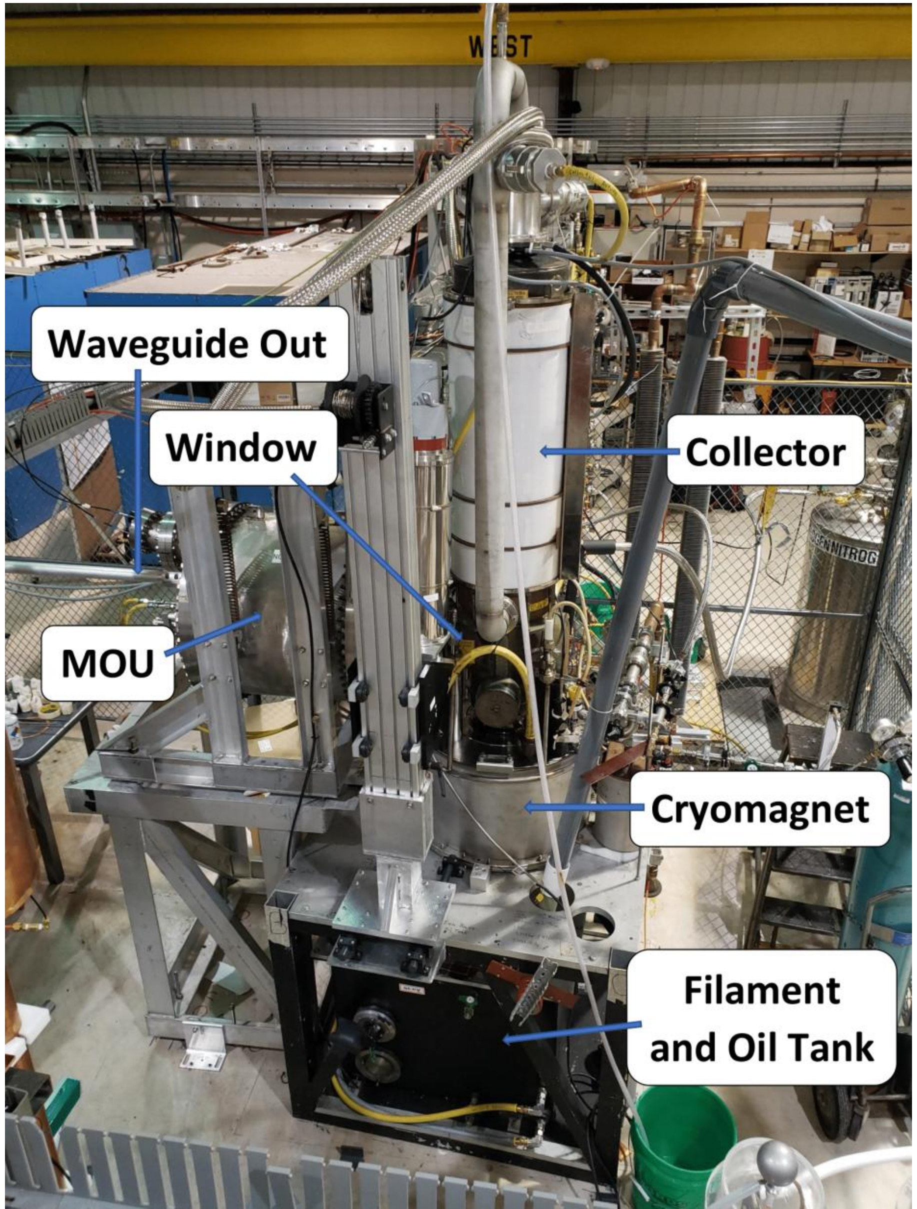
WHAM Systems Overview



Boris the Gyrotron

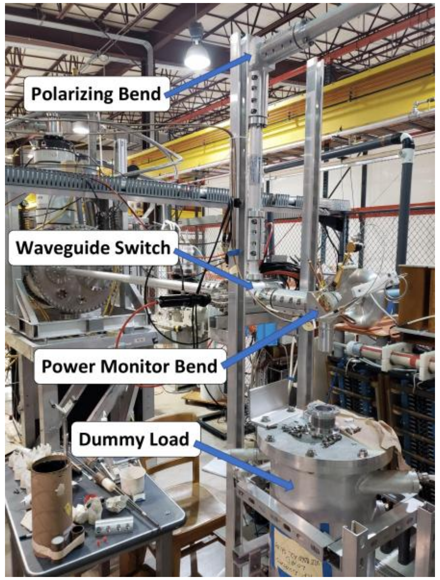
- 110GHz, 2s, 1MW class Centaur Gyrotron
  - GA -> KSTAR -> Storage -> WHAM
  - Run for 5-10 ms pulses
  - Power into plasma ~500kW

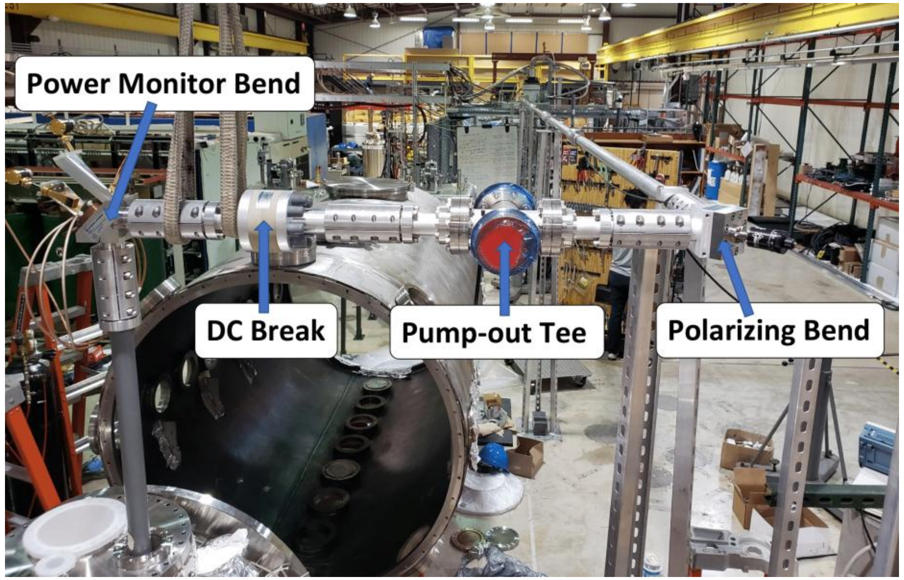


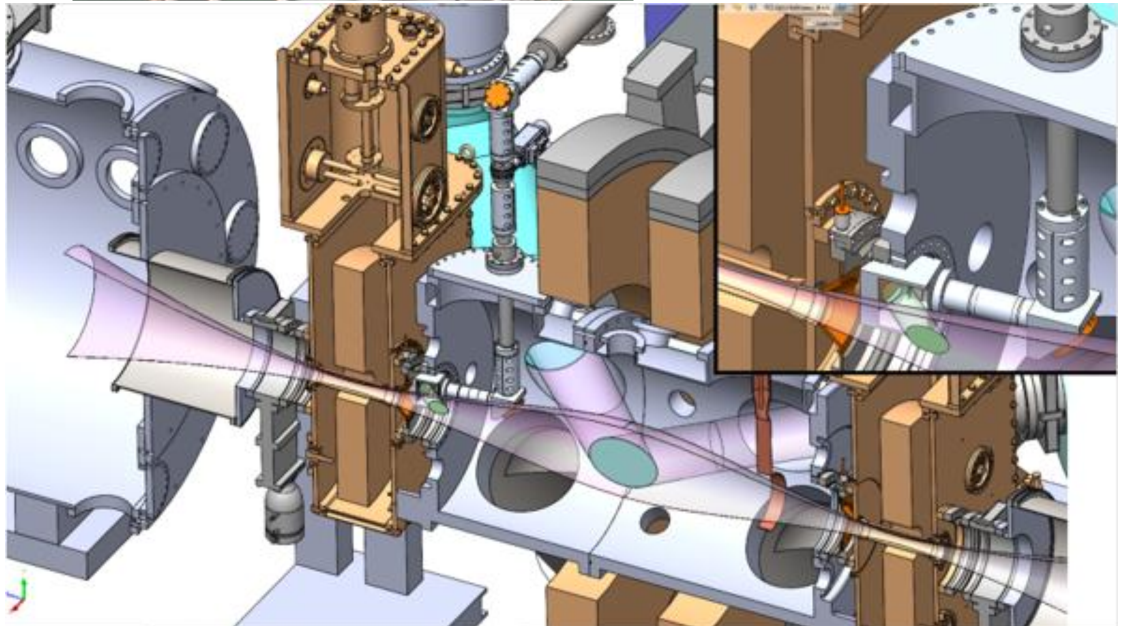


Waveguide Transmission Line

- 1.25” Corrugated waveguides
- 2 Polarizing miter bends
  - Verified to produce arbitrary polarization
- Waveguide and Vessel power monitors
  - Calibrated with a microwave calorimeter

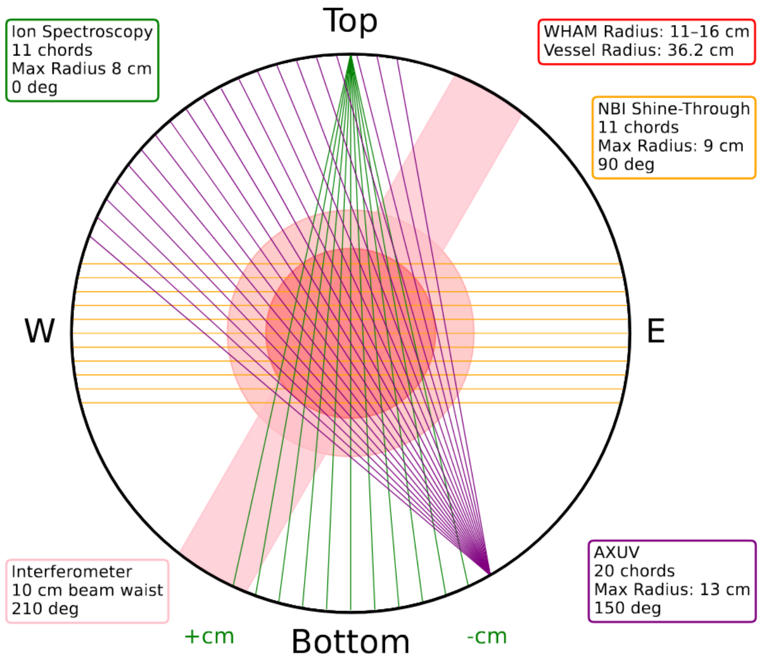


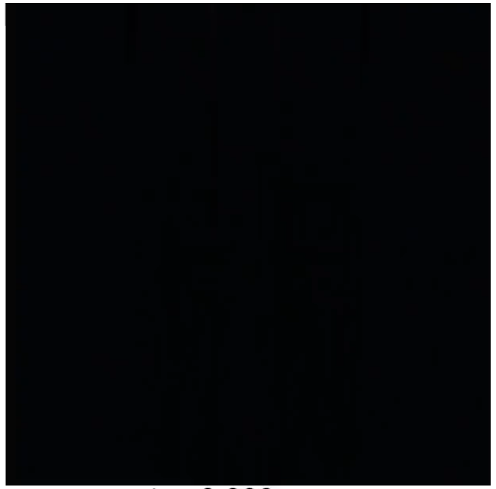




Relevant Diagnostics

- ECH Power Detectors
  - F-Band Diodes
- Microwave Interferometer
  - Single chord
  - 15 MHz IF Frequency
- Flux Loops
  - 0.08m, 0.35m, 0.62m
- Hard X-ray Detector
  - 25keV - 500keV
- Fast Visible Camera





t = 0.000 ms

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  - X1 Plasma Breakdown and HEI
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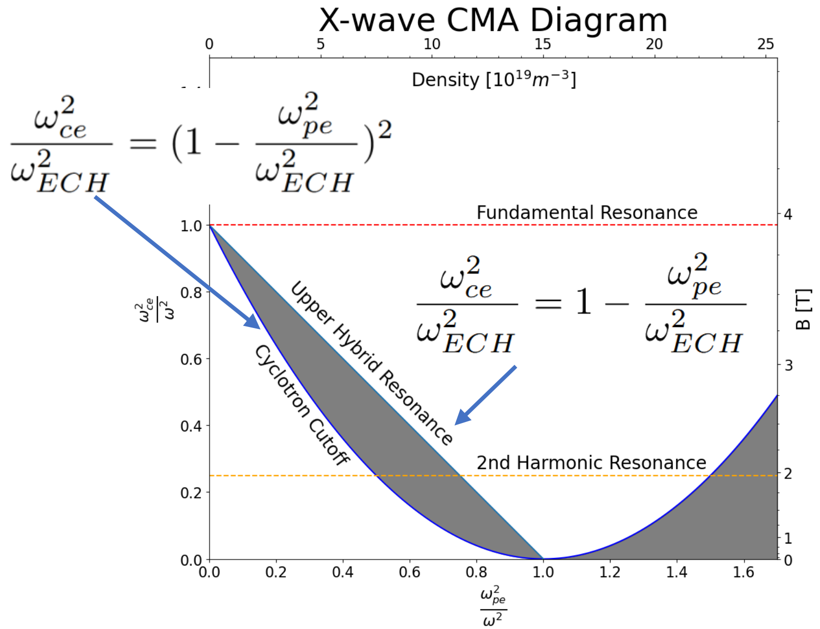
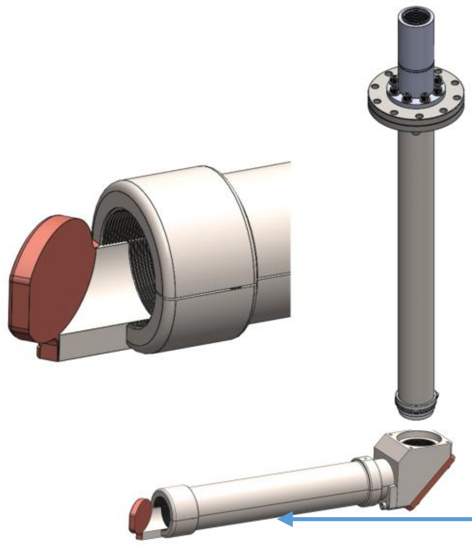
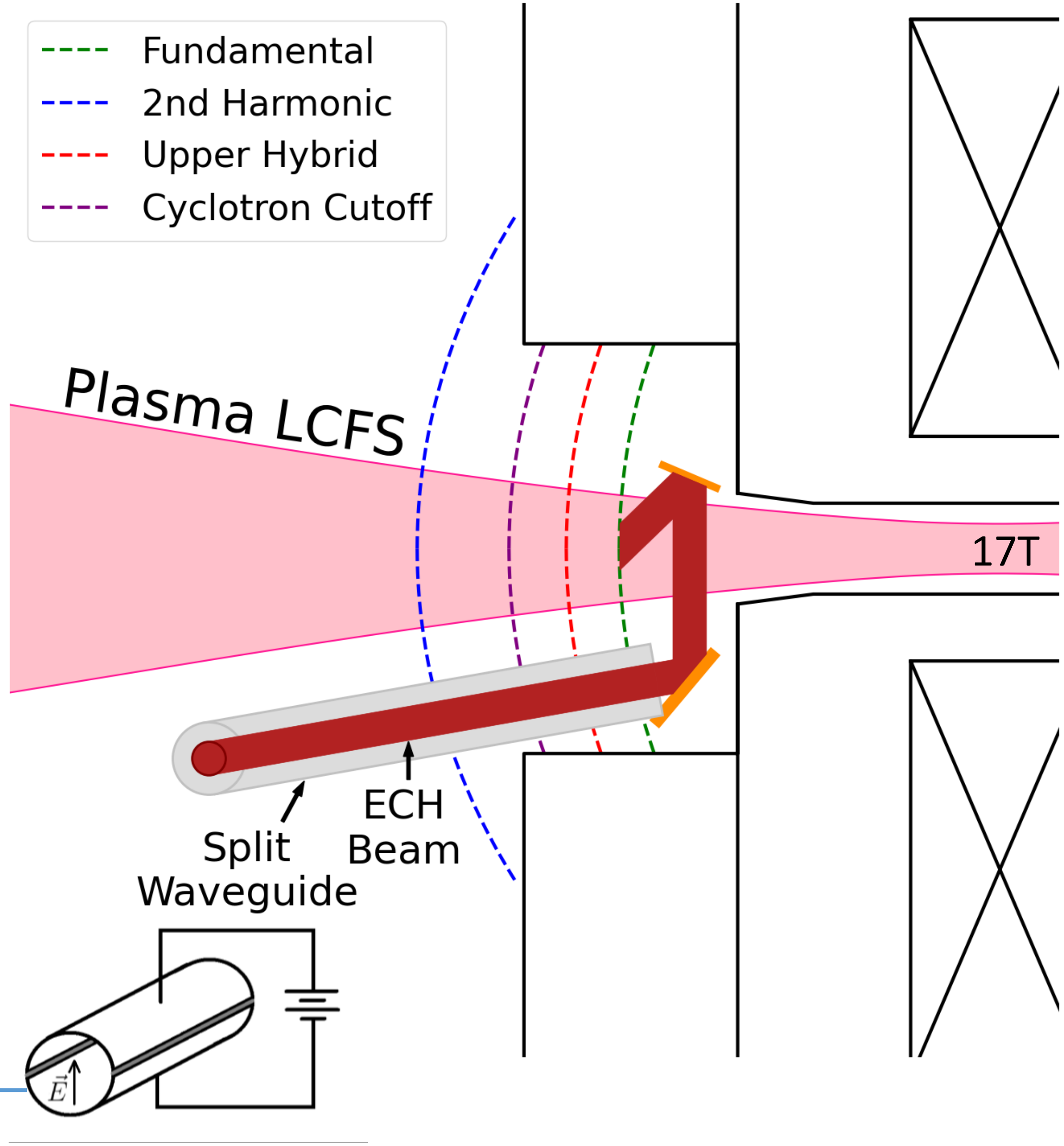
  - WHAM-R modifications
  - X2 Plasma Breakdown
  - O1 Plasma Breakdown

X1 Transmission Line and Mirror System

- X1 must be launched from the High Field Side (HFS)
- Split waveguide used to avoid in-waveguide breakdown
- Two mirrors reflect beam back towards resonance

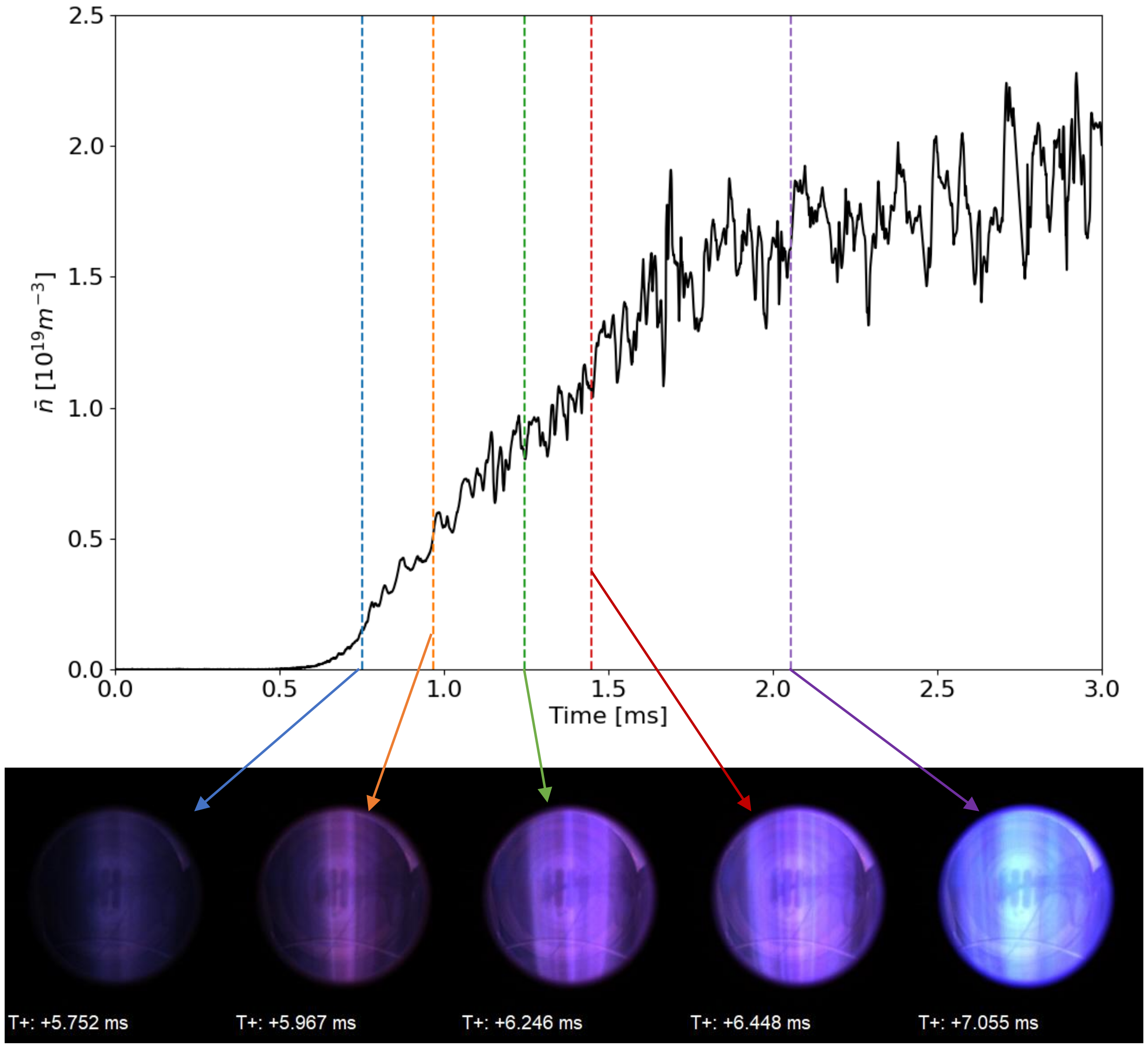






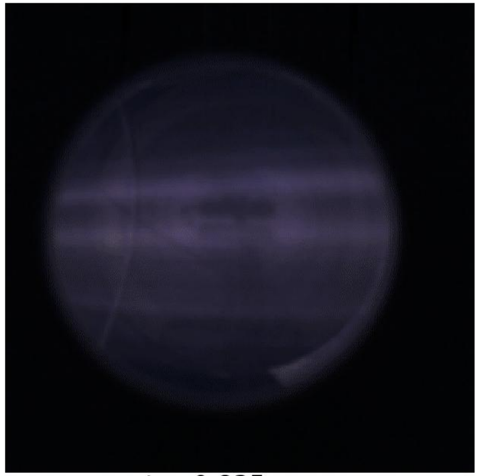
X1 ECH Reliably Produces Plasma

- 1-2 ms breakdown timescale
- Densities controllable with gas puff*
  - 1E18 - 1E20 m^{-3}
  - *After vessel conditioning
- No lower limit has been found for ECH breakdown power
  - Tested down to 20 kW
- Allows for breakdown of entire plasma column despite focused ECH beam
  - Plasma diameter at 4T ~7 cm
  - ECH diameter at 4T ~1.5 cm

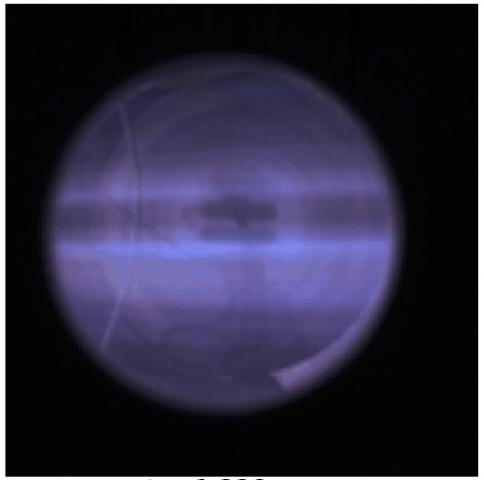


Hot Electron Instabilities Observed During Breakdown

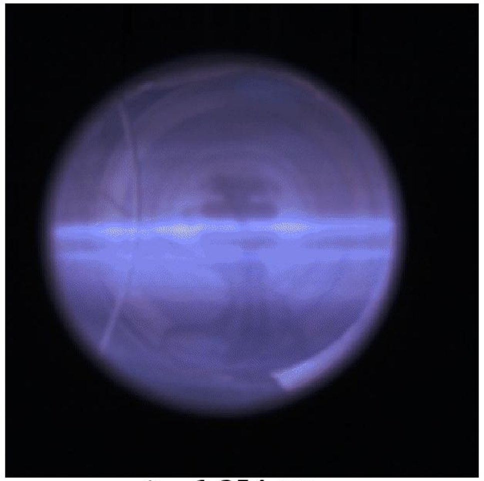
- High speed visible light camera shows radial transport in breakdown plasma
- Significant x-ray flux observed at the same time
- Hot electrons appear to stabilize after plasma buildup
  - HEI no longer visible on fast camera
  - X-ray flux also significantly reduced
  - Points to a n_{hot}/n_{bulk} limit



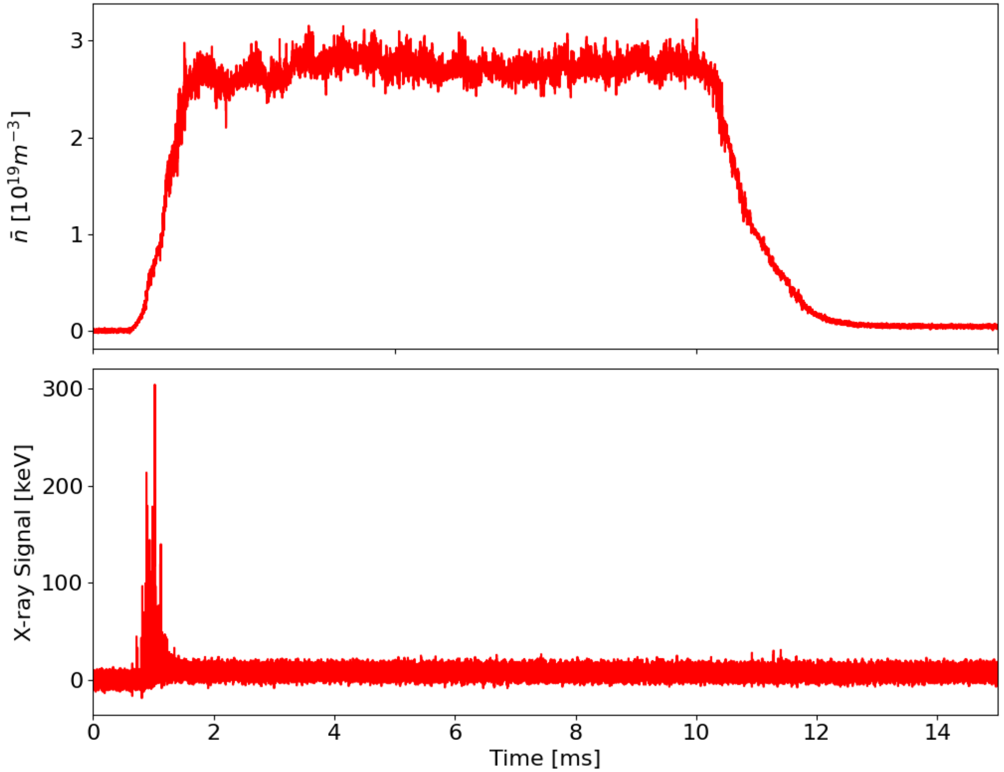
t = 0.835 ms



t = 1.228 ms

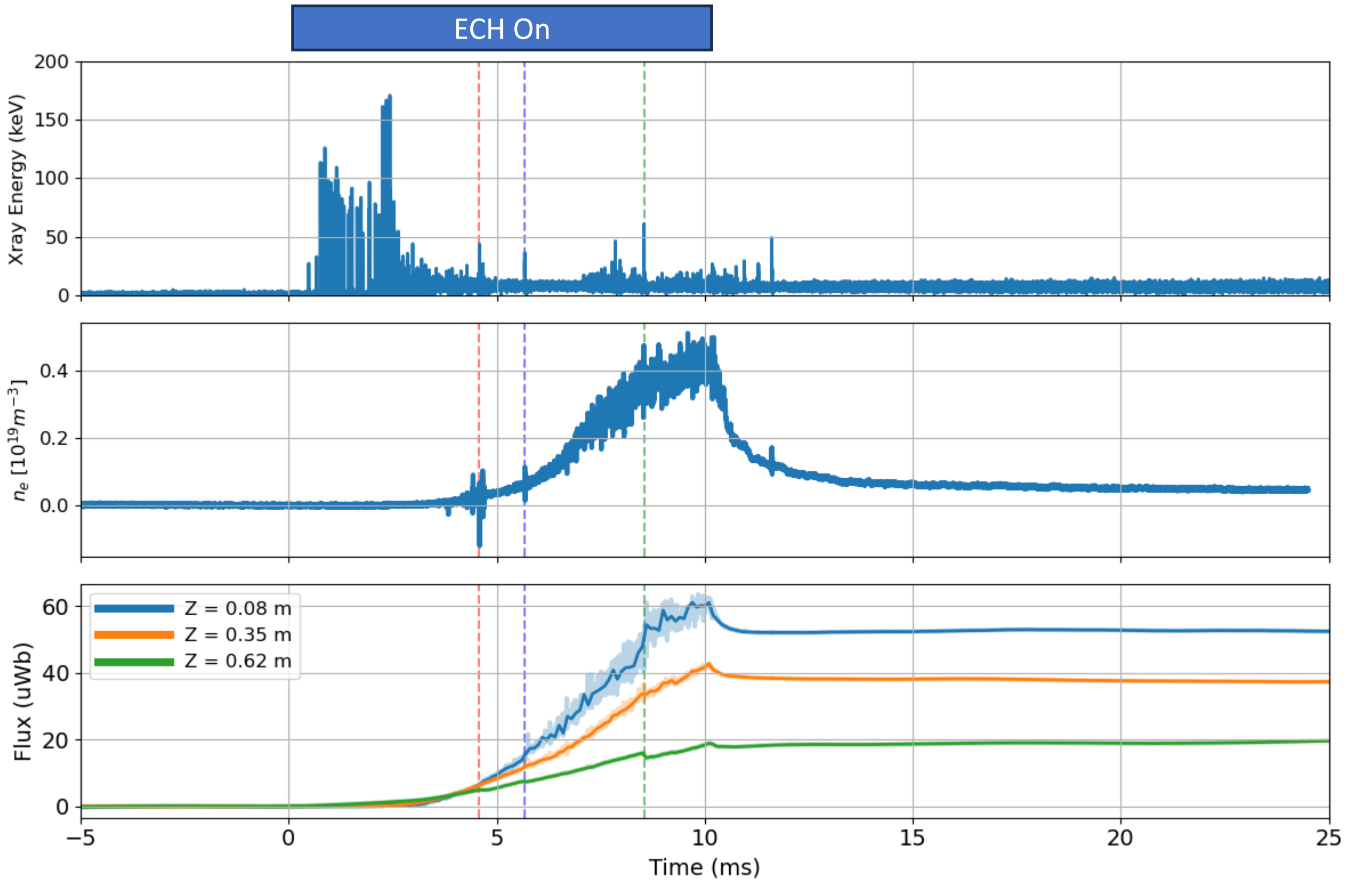


t = 1.354 ms



HEI events are seen during plasma

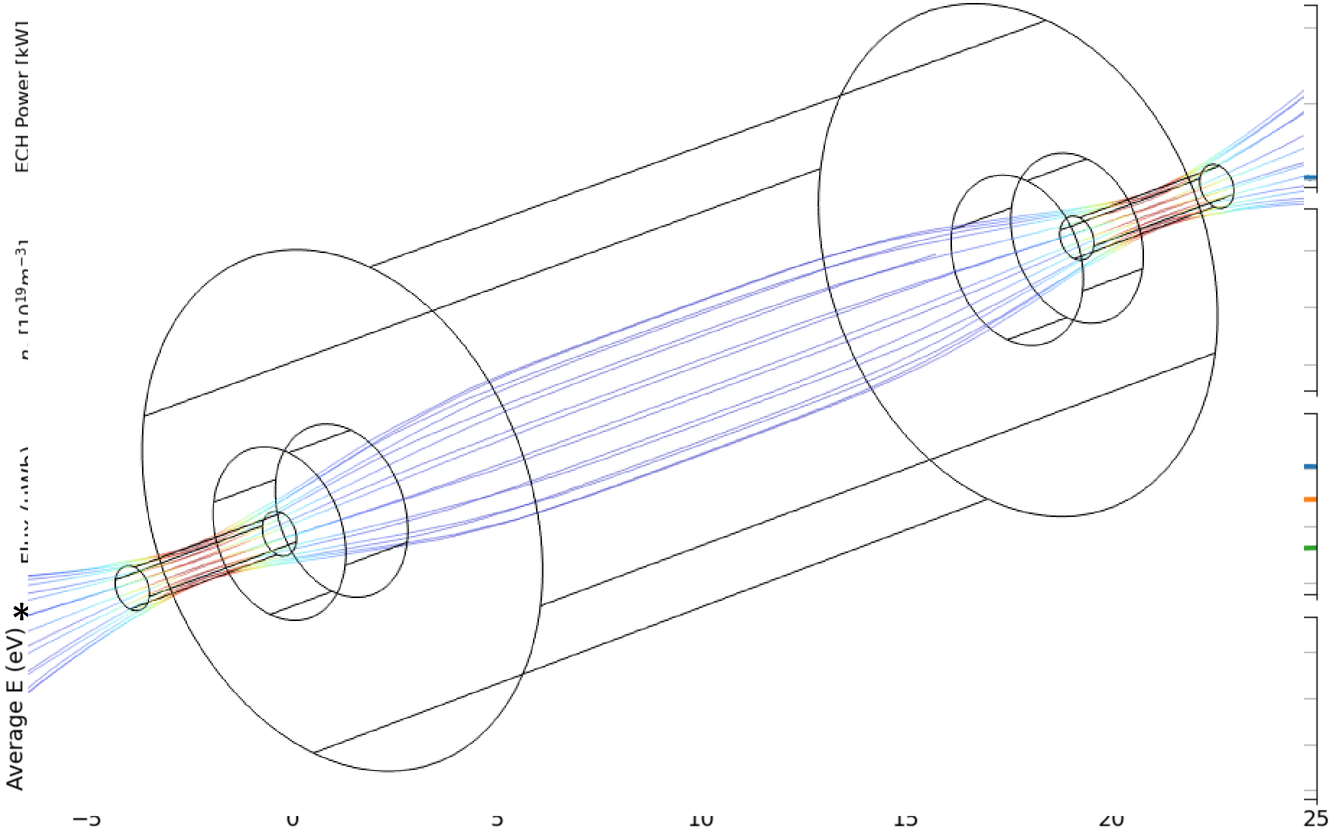
- At low density, HEI events are occasionally seen during shots
  - Most common in afterglow
- Characterized by sudden x-ray emissions, density fluctuations, and a dip in flux loop reading near sloshing e⁻ turning point
- These are likely the same type of events which drive plasma breakdown



Hot electrons observed in afterglow

- In lower density plasmas (<1E19), a large portion of flux remains after ECH ends
- Very small density also remains
- Thought to be mainly high energy, sloshing electrons
  - Turning point near 4T resonance
- Not observed in high density or NBI fueled plasmas
  - Potentially killed by high neutral pressure

Shot 250112017



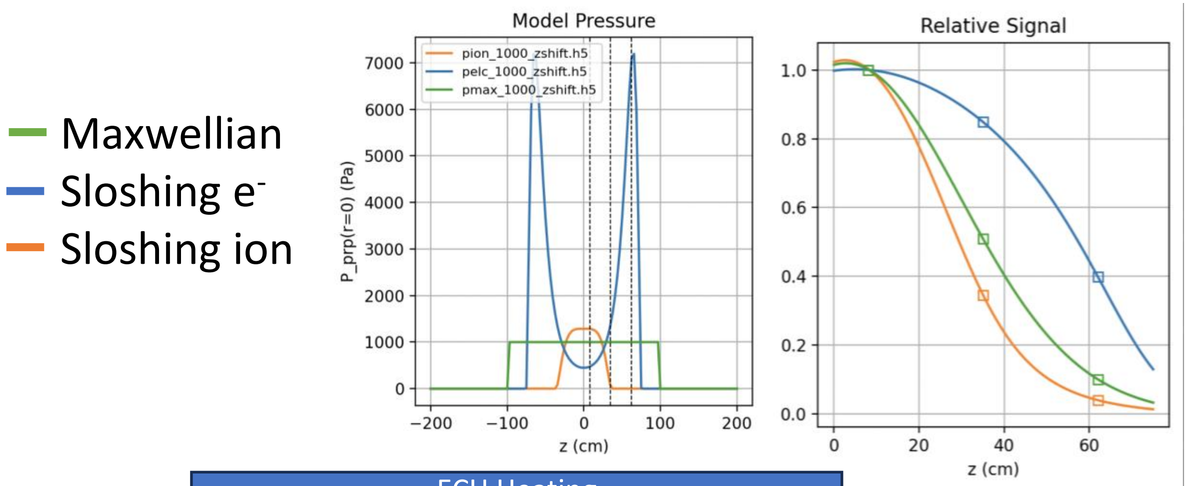
Larmor radius exaggerated for effect

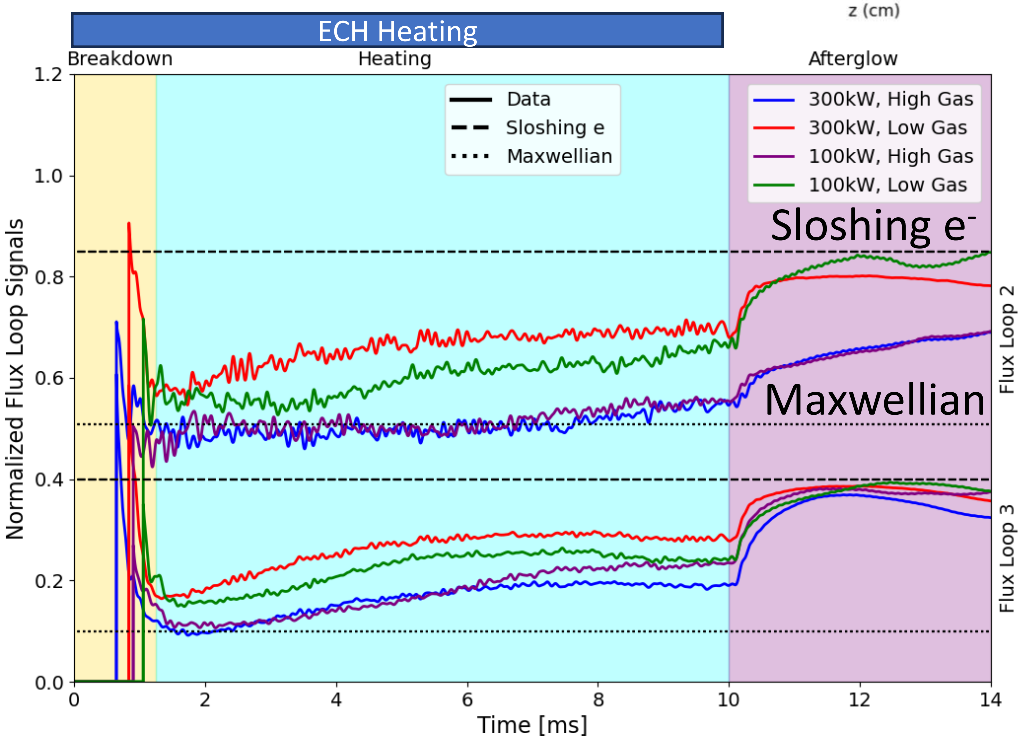
Actual radius of 500keV electron ~0.7mm at turning point

*Rough estimate

Equilibrium Reconstruction Suggests Sloshing Electron Afterglow

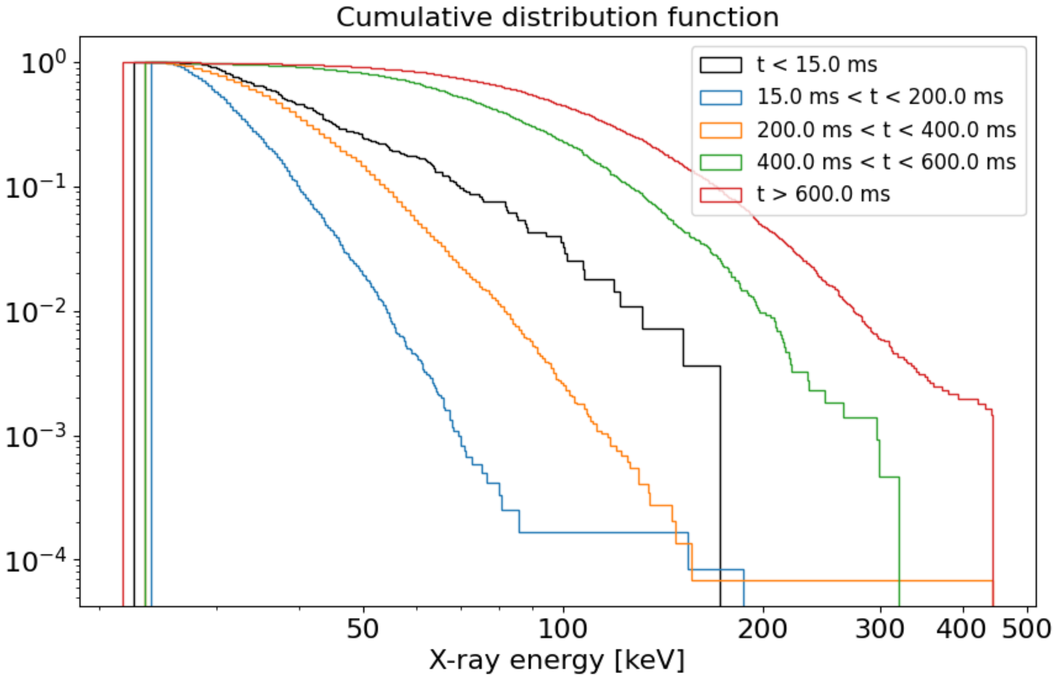
- Plasma flux can be modeled as the sum of 2 basis functions
  - Maxwellian, Sloshing e^-
  - Sloshing ion not relevant without NBI
- During breakdown, plasma is dominated by sloshing electrons
- In the "heating" phase, X1 ECH preferentially heats the sloshing population
  - Higher ECH power and lower neutral gas enhance this effect
- In the afterglow, sloshing electrons once again dominate flux

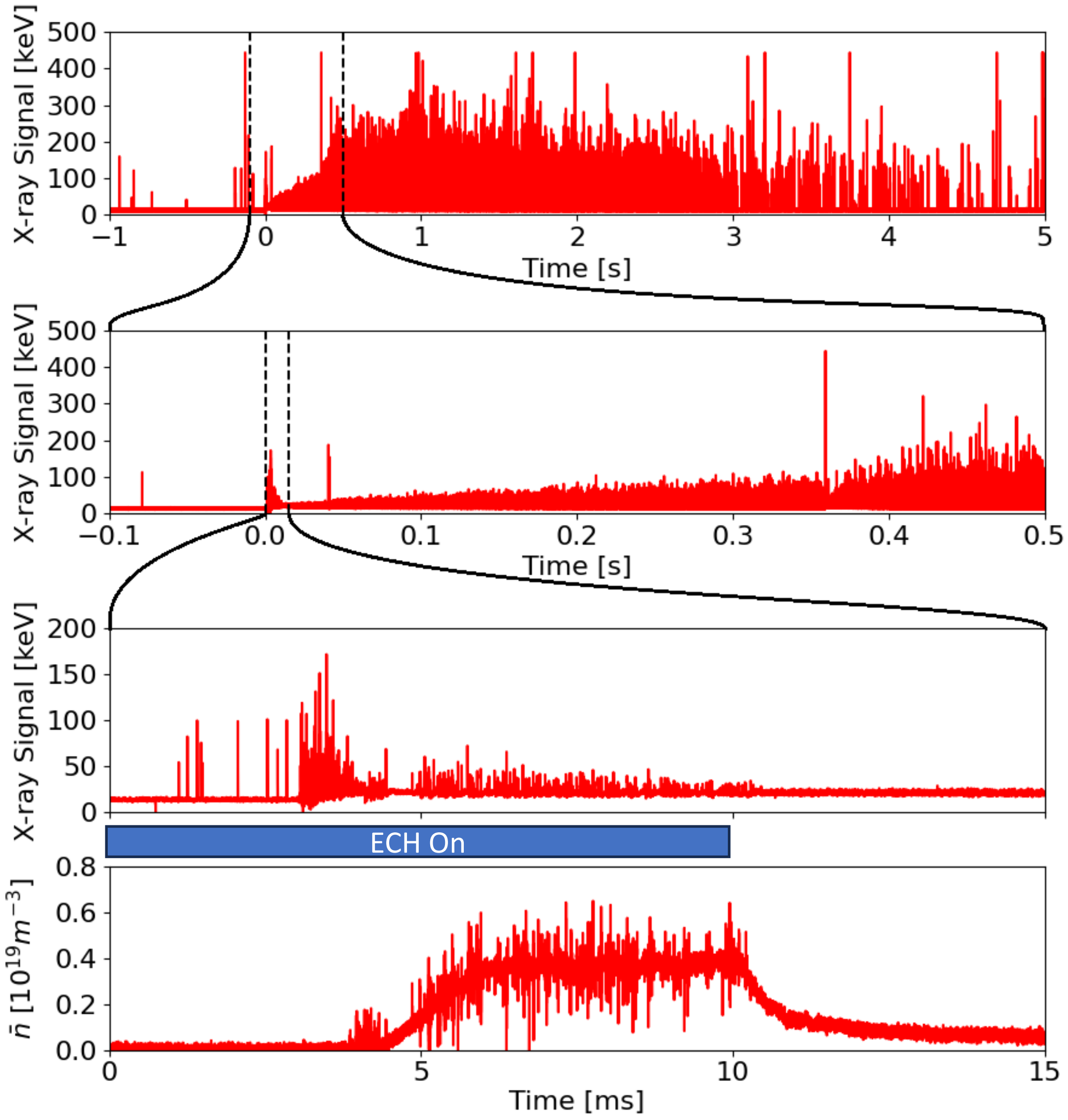




High Energy Electrons are seen thru X-ray Emission

- Hard X-rays seen on every shot
  - Energies > 100 keV
  - Initial burst during breakdown
  - Majority are seen seconds after shot
  - X-ray energy increases with time
    - Afterglow electrons are classically confined





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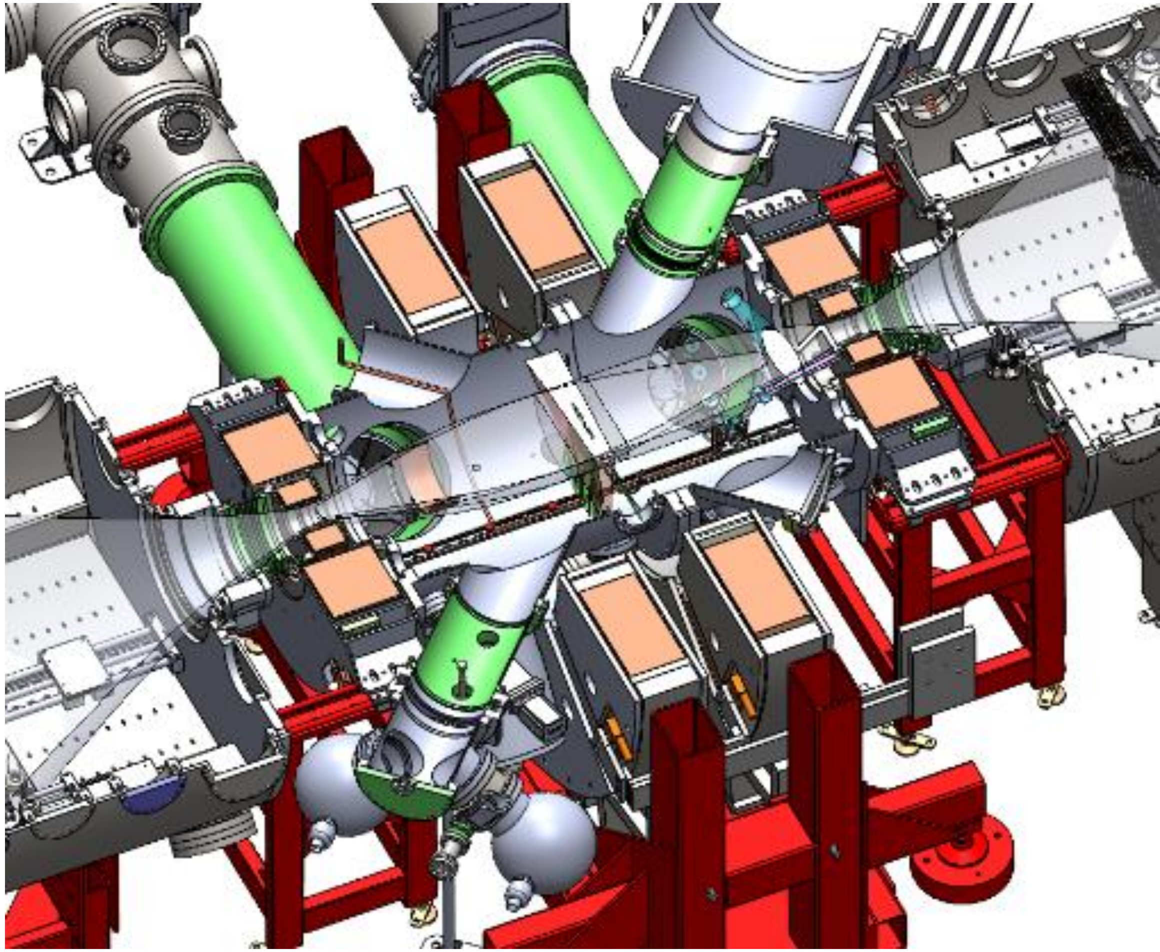
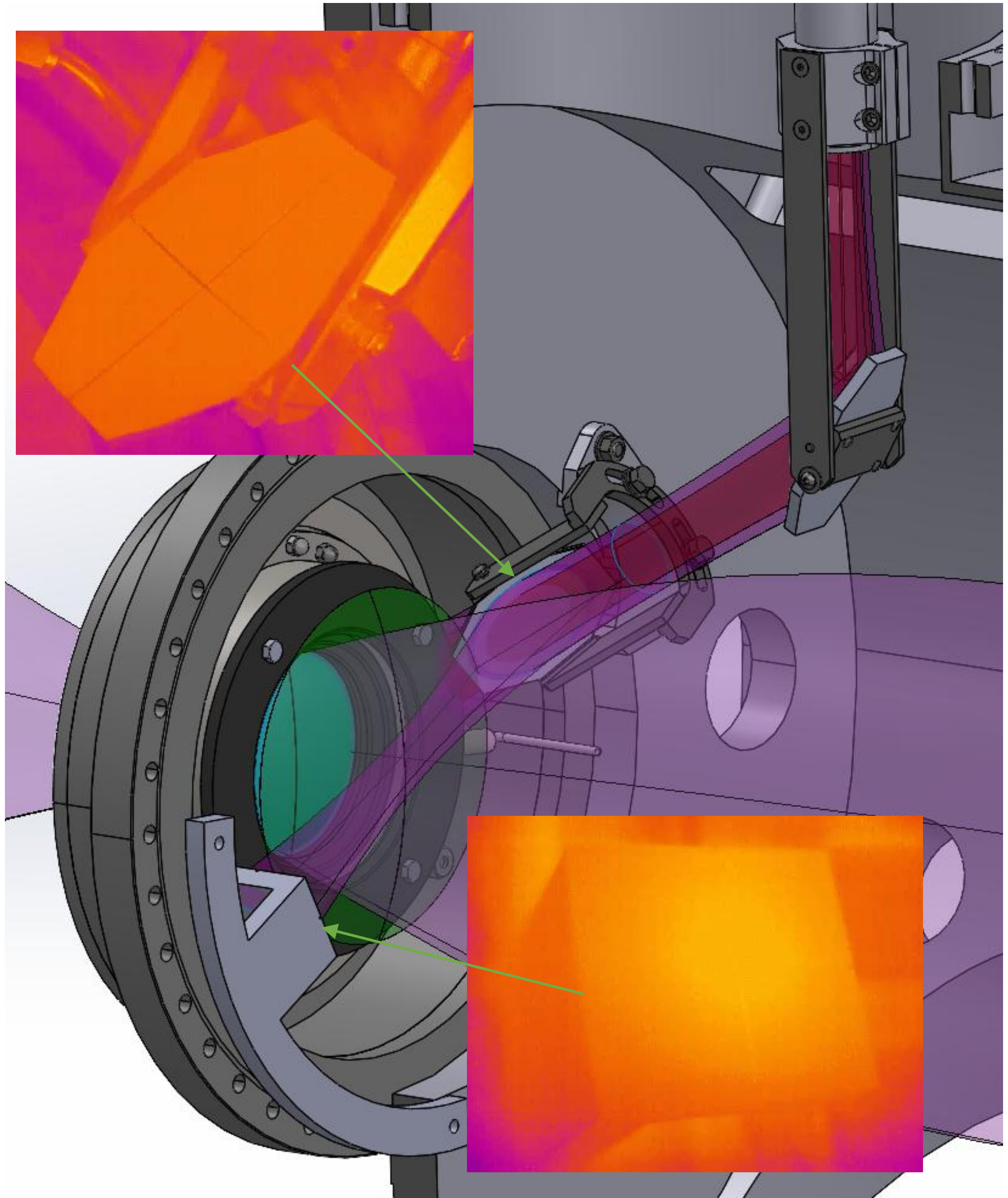
WHam Anvil-like Mirror-Ratio (WHAM-R)

- During HTS magnet maintenance, (now complete), WHAM has been converted into a pulsed copper machine
  - HTS magnets replaced with 20kA outer magnet and 6kA insert coils at each end
  - Central W7 coils energized to 10kA each
- Parameters compared to WHAM
  - B_{max} = 17T -> 7.1 T
  - B_{min} = 0.25T -> 0.484 T
  - R_m = 68 -> 14.7
  - D_{cen} = 30cm
- Fundamental ECH resonance becomes inaccessible for HFS launch
  - Instead X2 and O1 are being explored as breakdown options



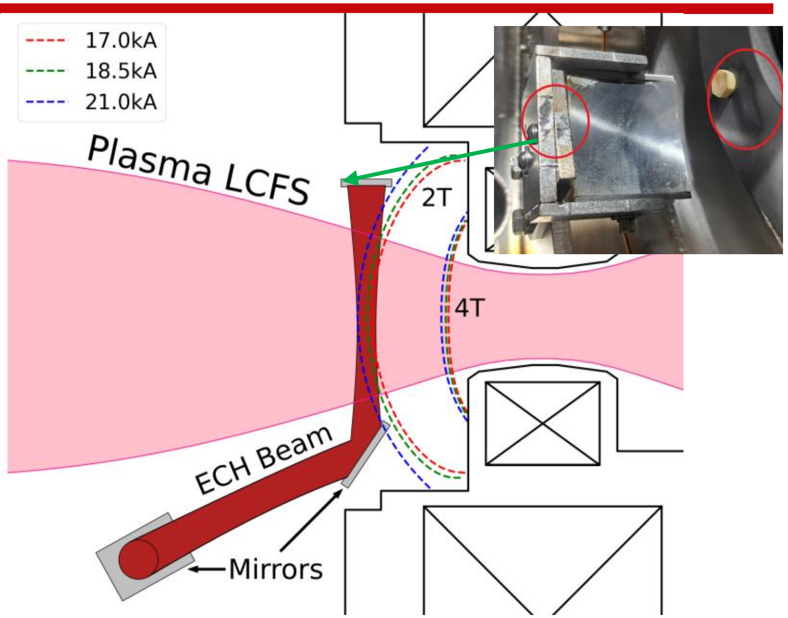
X2 and O1 are more accessible than X1

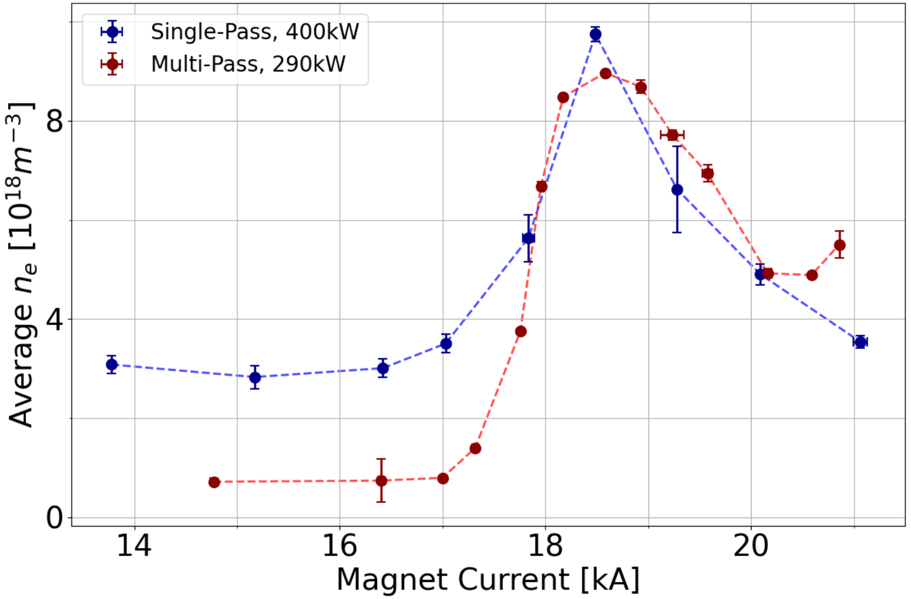
- Cyclotron cutoffs are no longer an issue
  - No split waveguide to get to HFS
- ECH is transmitted fully optically
- Elliptical mirrors allow for a minimal beam waist at resonance
  - Verified by thermal videos during alignment
- Beam path allows for multiple passes with additional mirrors
  - Tested with some success



Magnetic field scan shows first pass X2 breakdown

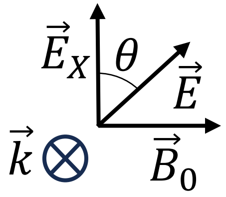
- Magnet current was scanned to move resonance across ECH beam path
- Density peaks when resonance is on beam axis
  - Due to 1st pass X2 breakdown
- Density flattops at ~3E18 when resonance is out of beam path
  - Due to stray ECH breakdown
  - Could be fundamental or 2nd harmonic
- Multi-pass configuration allows for higher density at lower power
  - Some issues with reflection back into waveguide

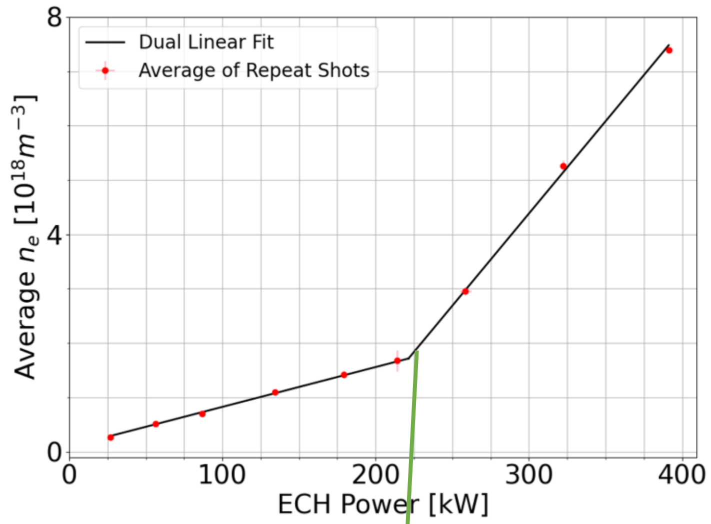


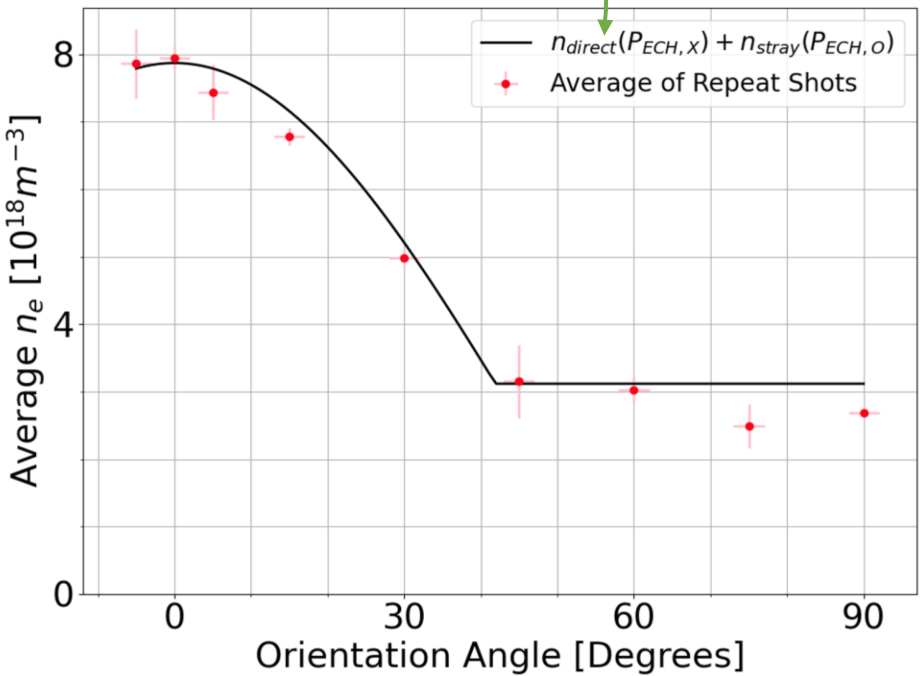


Polarization scan supports X-mode absorption

- First polarization is set to X-mode and the power dependance was measured
  - Clear slope shift around 225kW
  - May suggest a minimum density for significant X2 absorption
- Next, polarization angle was scanned from X to O mode at 400kW power
  - Density peaks at X mode, as expected
  - Flattop starts at ~50% X mode, corresponding to ~225kW of X mode power

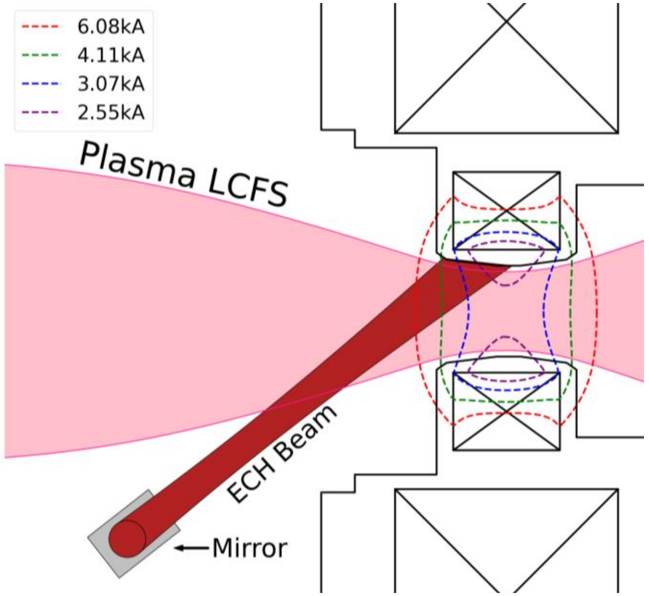


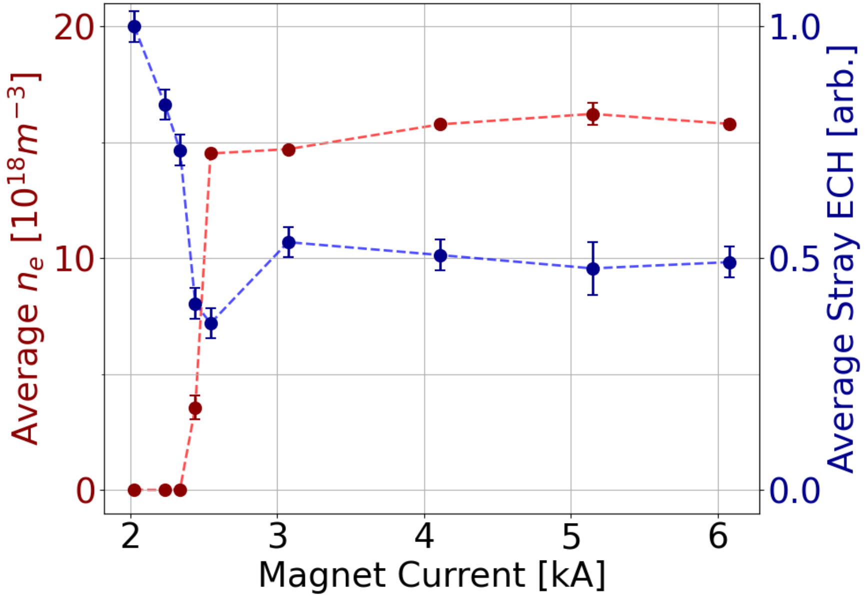




O1 works when the resonance exists

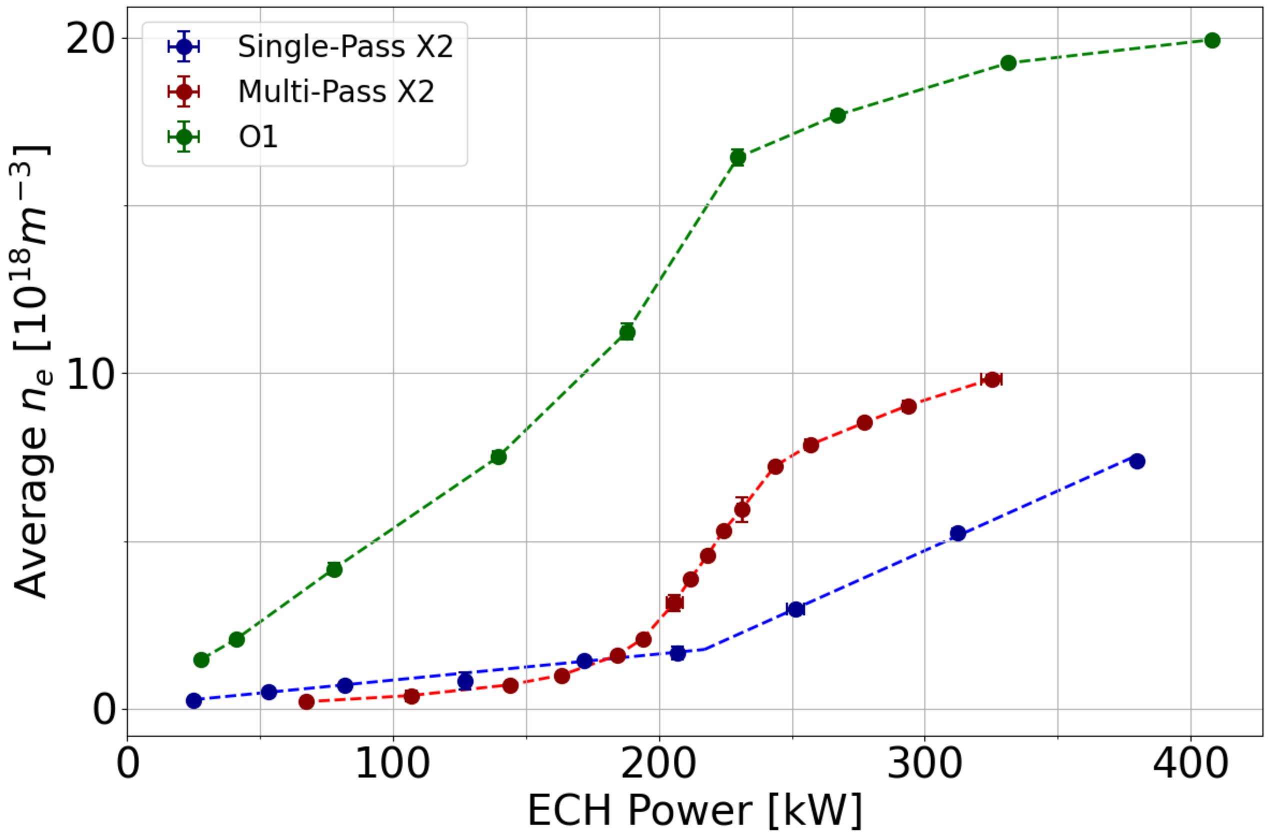
- O1 breakdown largely independence of contour location
- Reaches higher density than X2 at lower power
  - Higher absorption percentage at low density
  - Supported by ray-tracing simulation
- Drop in stray ECH power indicates significant power absorption
  - Not seen in X2 case
- Full ionization of plasma column is observed





Power scans reveal non-linear density growth

- In all configurations, density grows non-linearly with power
- Competing effects at work
  - Higher density -> higher absorption -> higher density
  - Higher density -> higher refraction -> lower absorption
  - Eventually gas is fully ionized
- Simulation is actively underway to model these processes



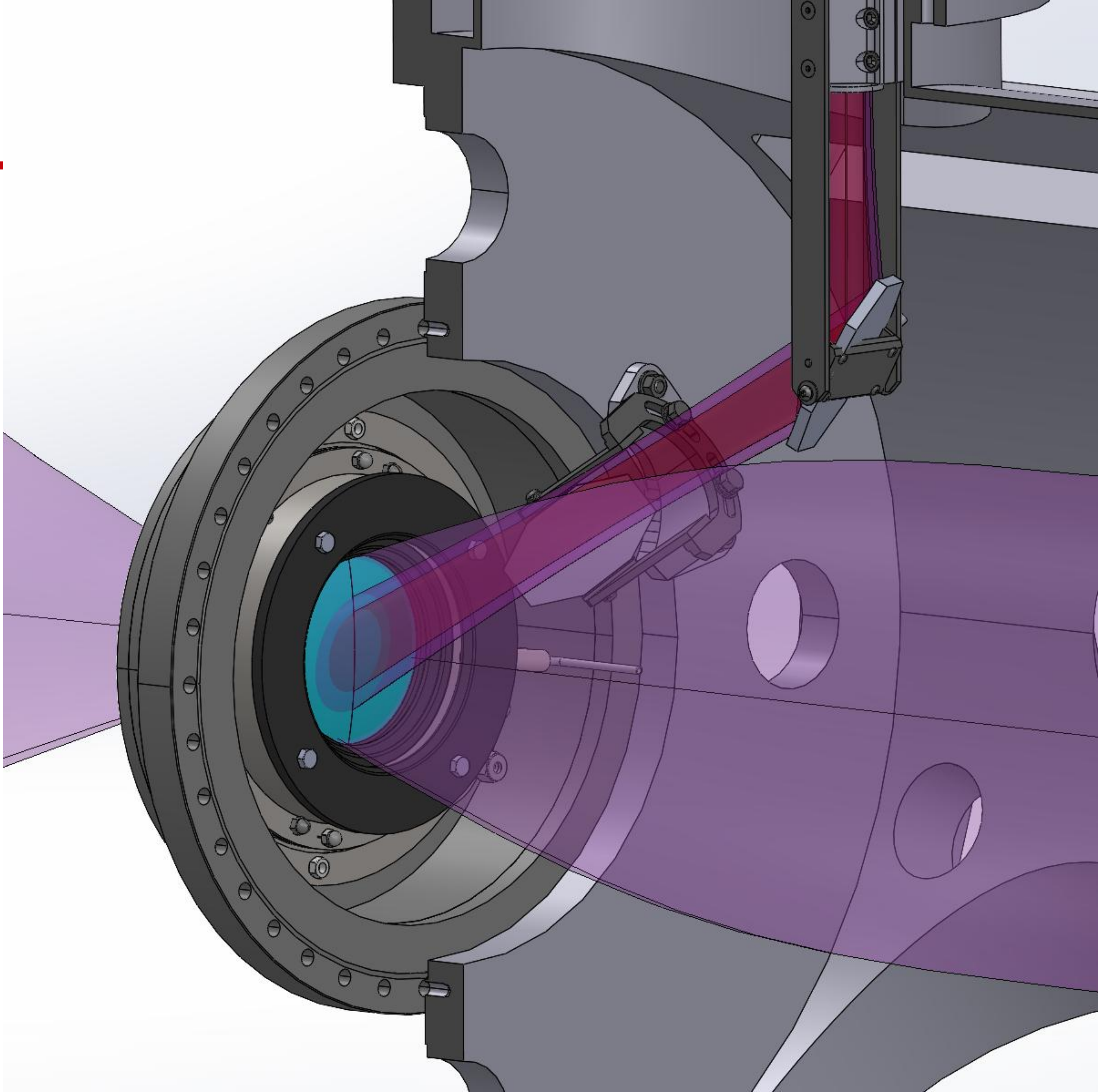
Conclusions

- WHAM can reliably achieve plasma breakdown using X1 ECH
  - Density can vary from 1E18 to >1E20 depending on gas puff
- During breakdown, radial transport is seen accompanied by bursts of high energy X-rays
  - This explains how a relatively small ECH beam can fully ionize plasma volume
- Additional X-rays are seen seconds after ECH heating ends
  - High energy (100s of keV) tail of electrons with very low collisionality
- WHAM-R has recorded densities >2E19 using X2 and O1 breakdown
  - First recorded X2 breakdown in a magnetic mirror
  - Allows for continued experiments in WHAM despite lowered field

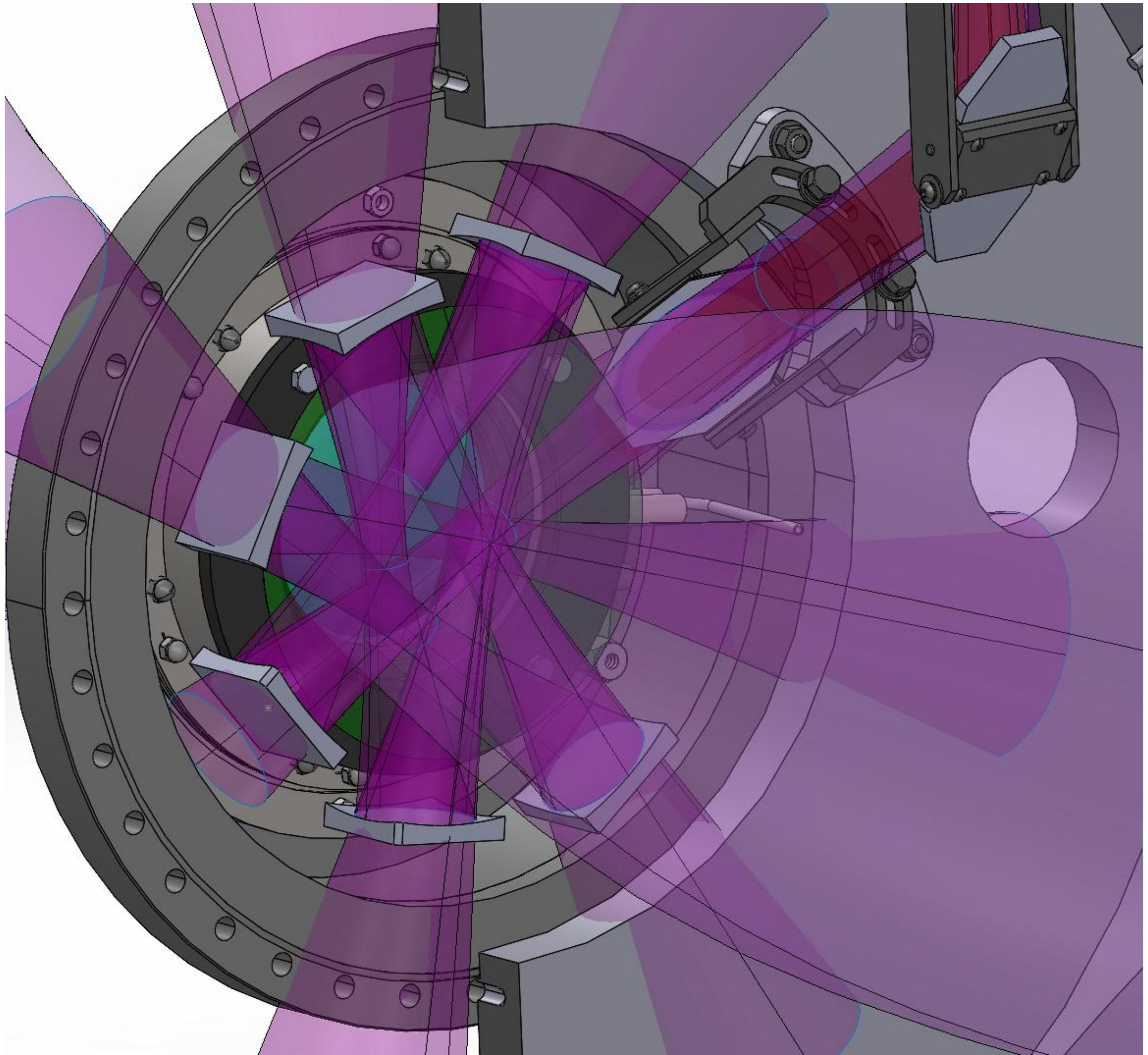
Questions?

Additional Slides

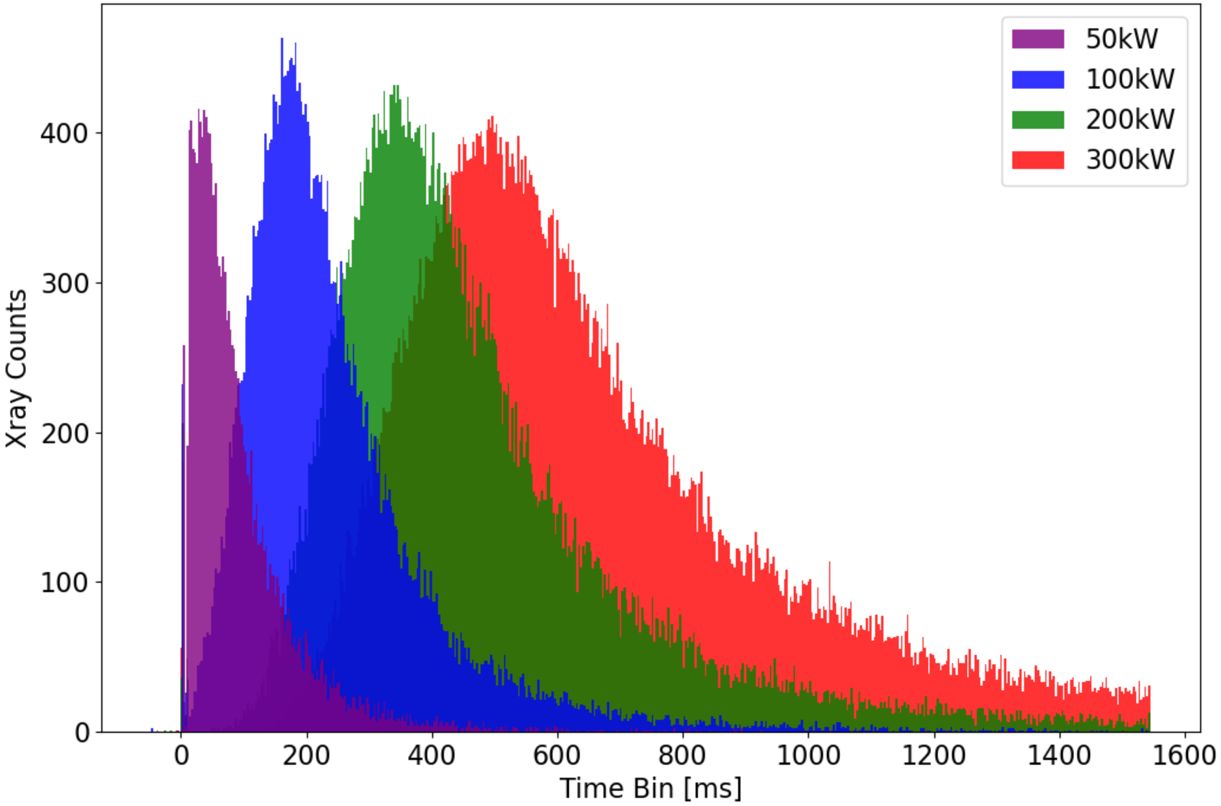
O1 Beam Path

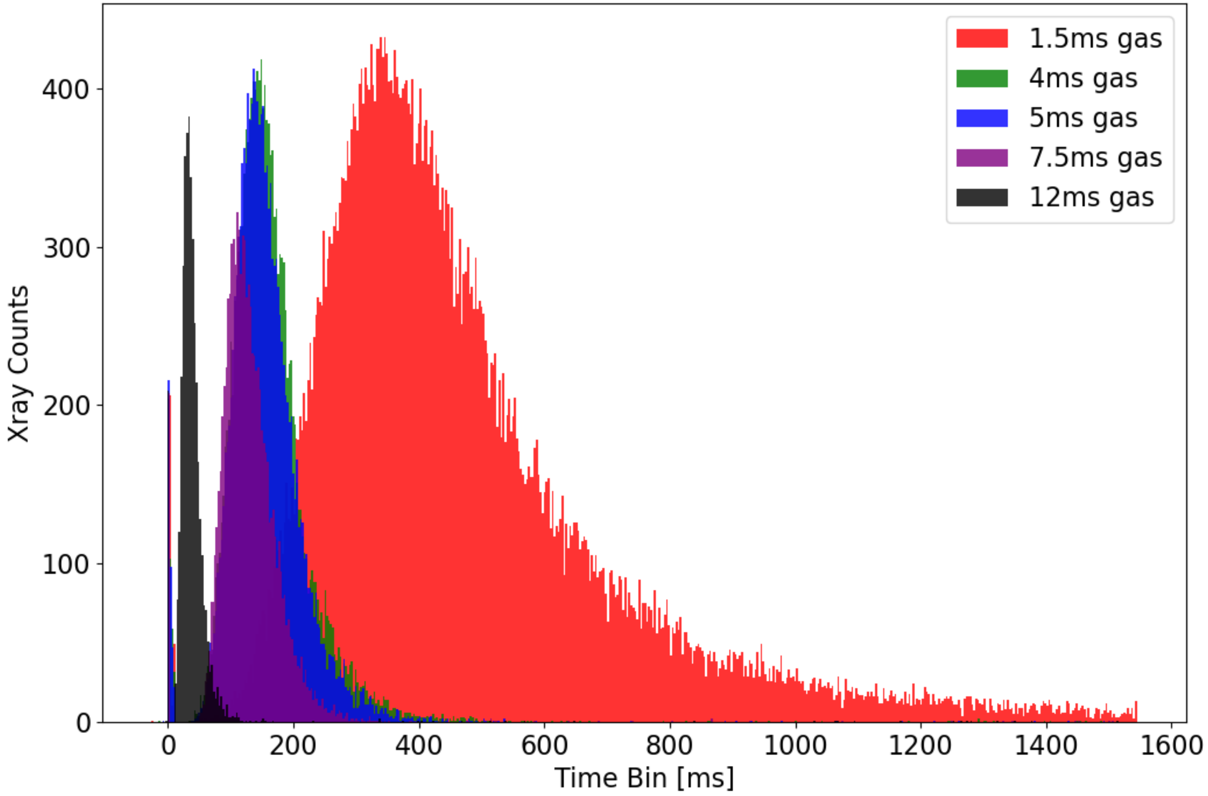


7 Pass X2 Mirror Array

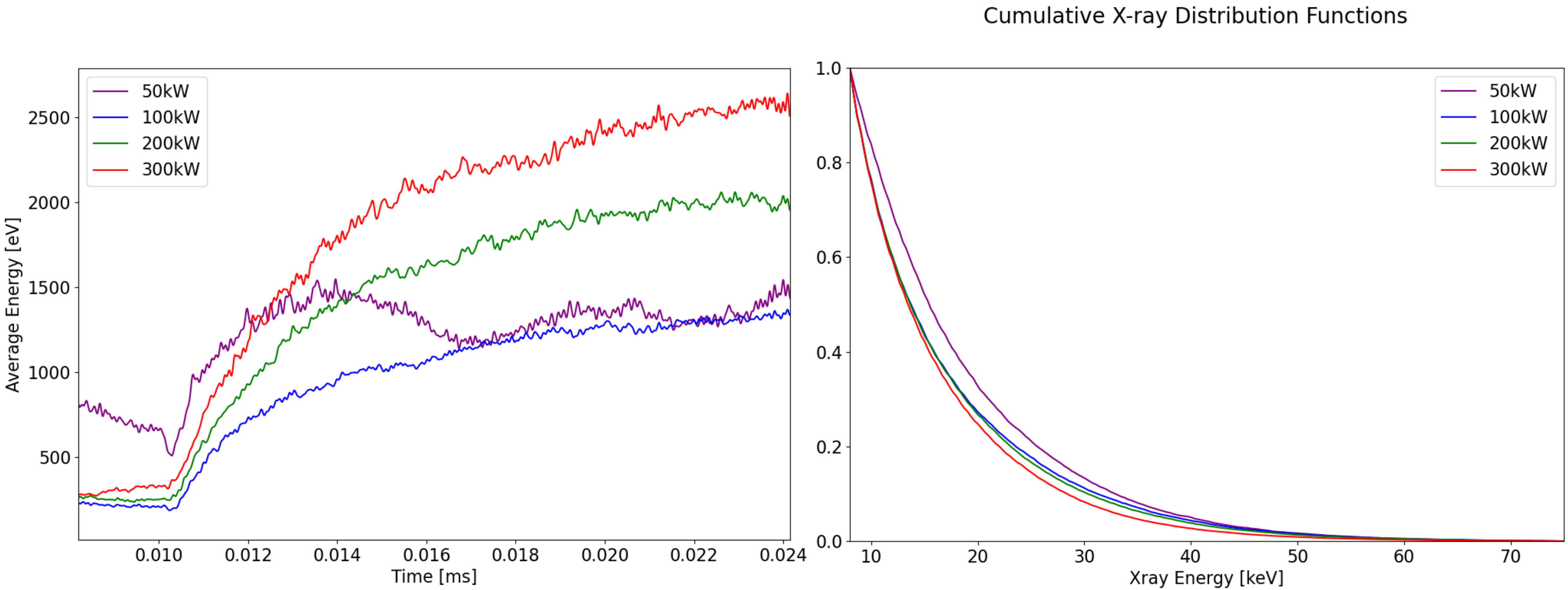


X-ray counts vs time



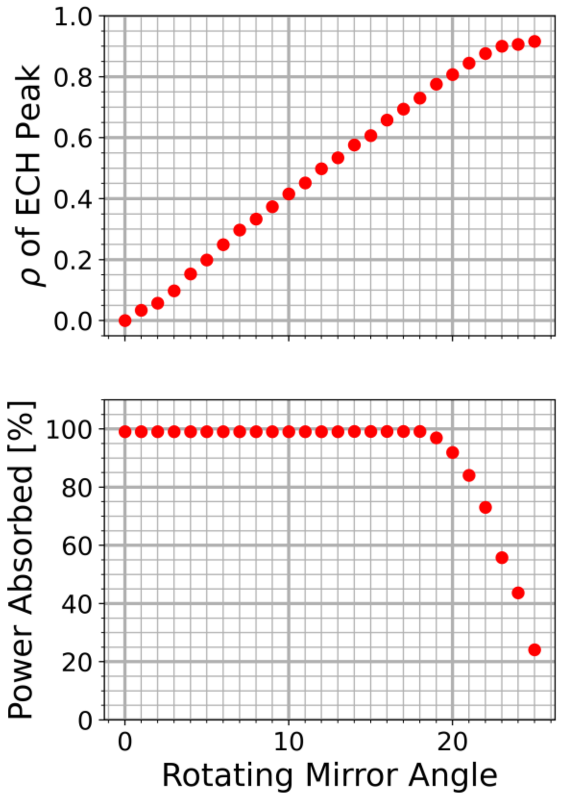


Distribution of X-rays anticorrelated with P_{ECH}

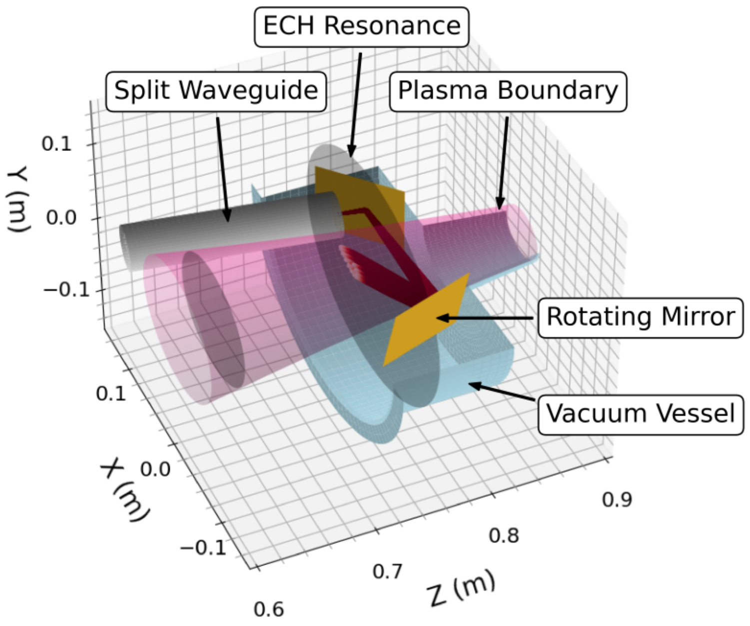


1.5ms Gas Puff

First Plasma

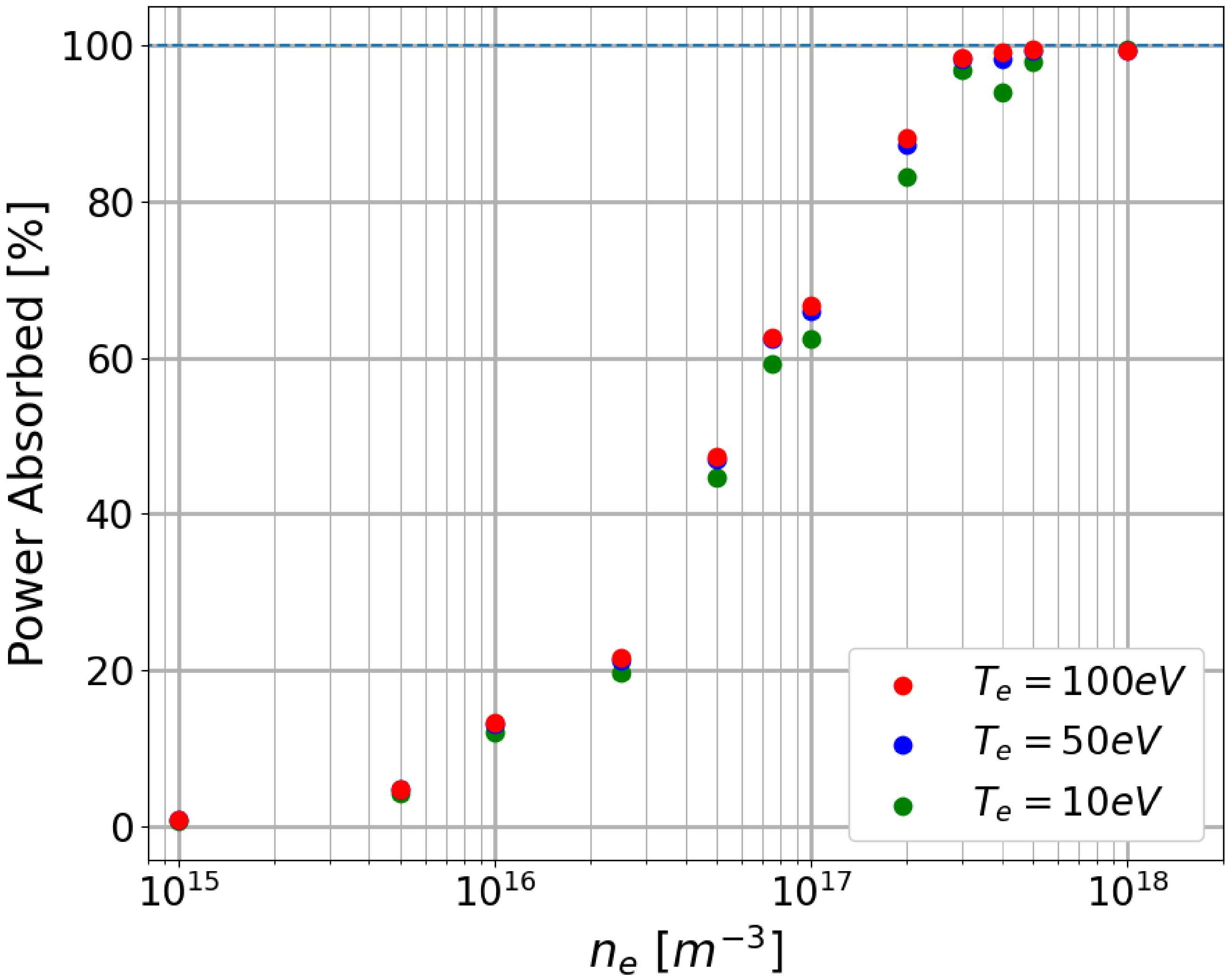


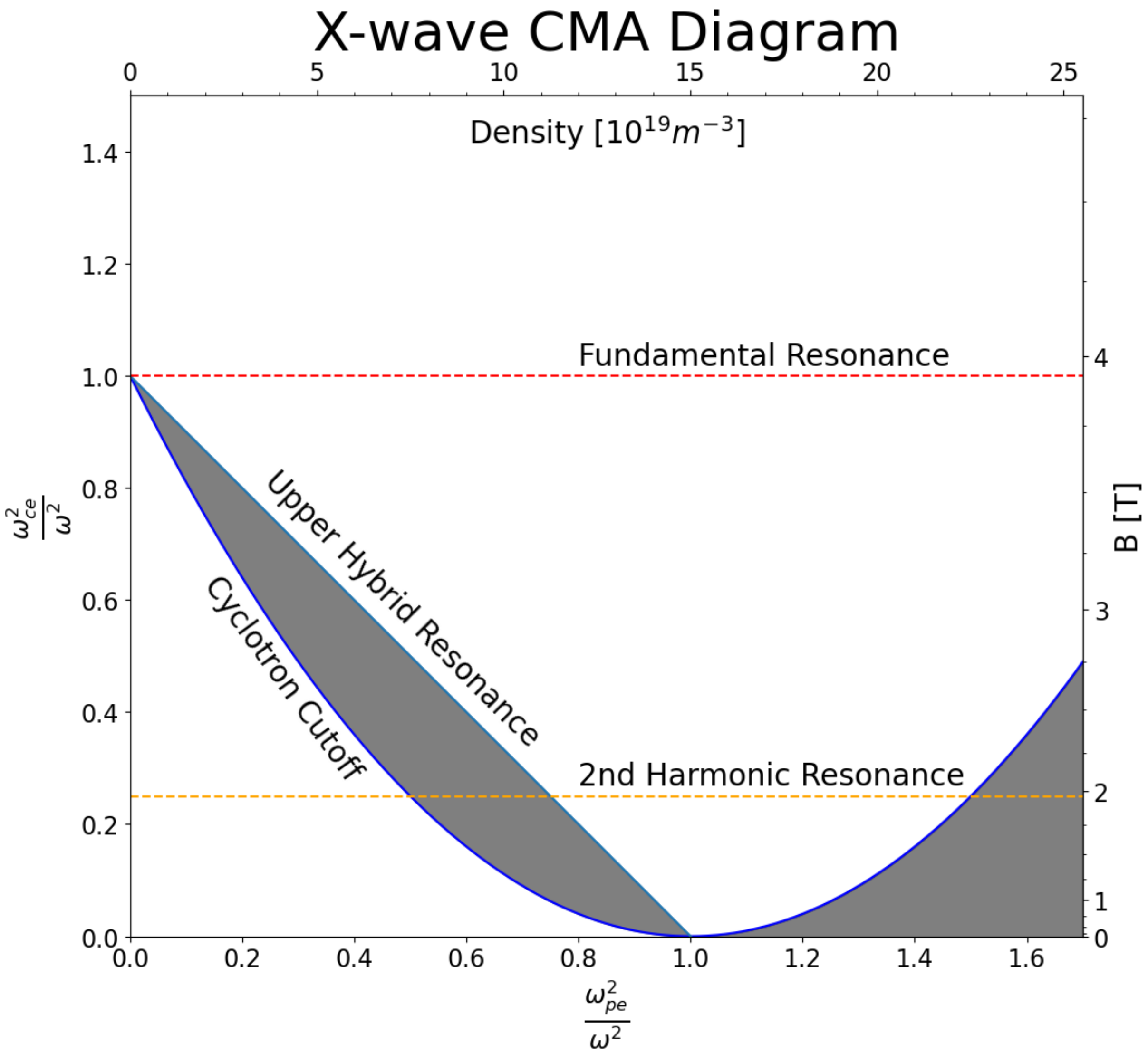
ρ of ECH Peak
Power Absorbed [%]
Rotating Mirror Angle



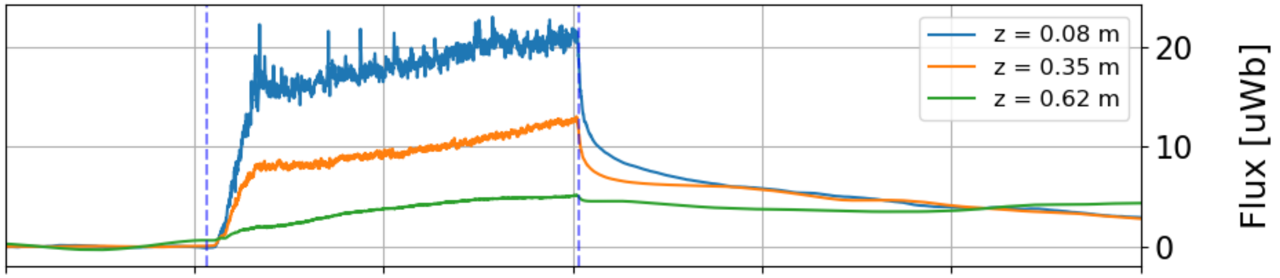
ECH Resonance
Split Waveguide
Plasma Boundary
Rotating Mirror
Vacuum Vessel
Y (m)
X (m)
Z (m)

X1 Absorption Genray Simulations

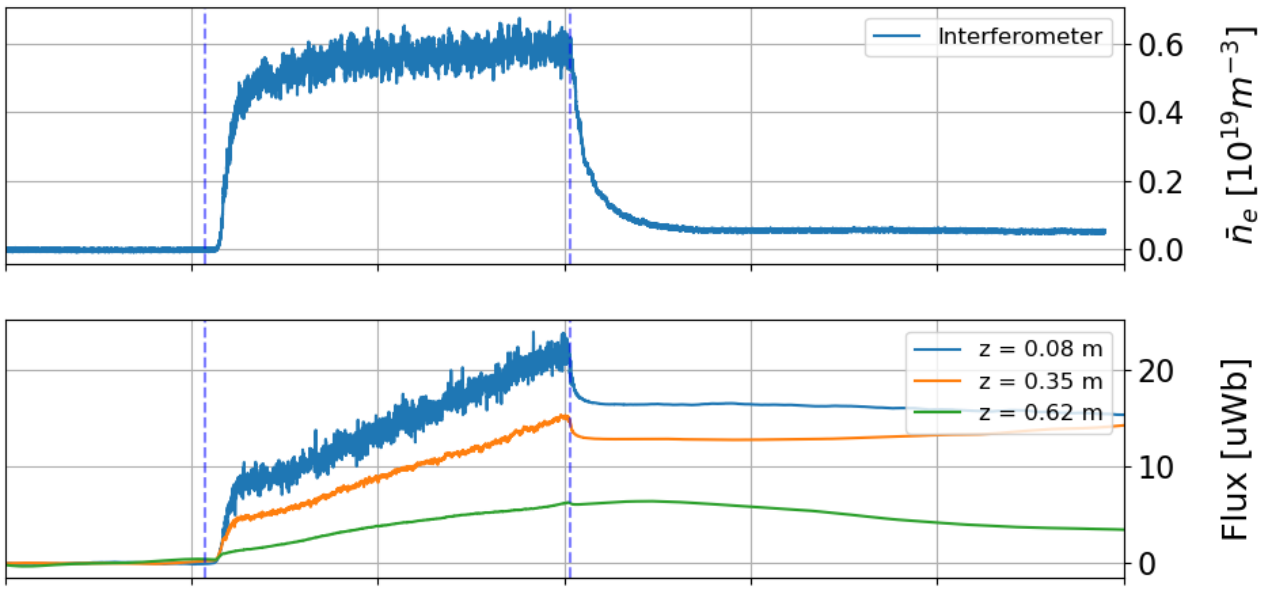



X-wave CMA Diagram
0
5
10
15
20
25
Density [$10^{19}m^{-3}$]
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$\frac{\omega_{ce}^2}{\omega^2}$
Fundamental Resonance
Upper Hybrid Resonance
Cyclotron Cutoff
2nd Harmonic Resonance
4
3
2
1
0
B [T]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
$\frac{\omega_{pe}^2}{\omega^2}$

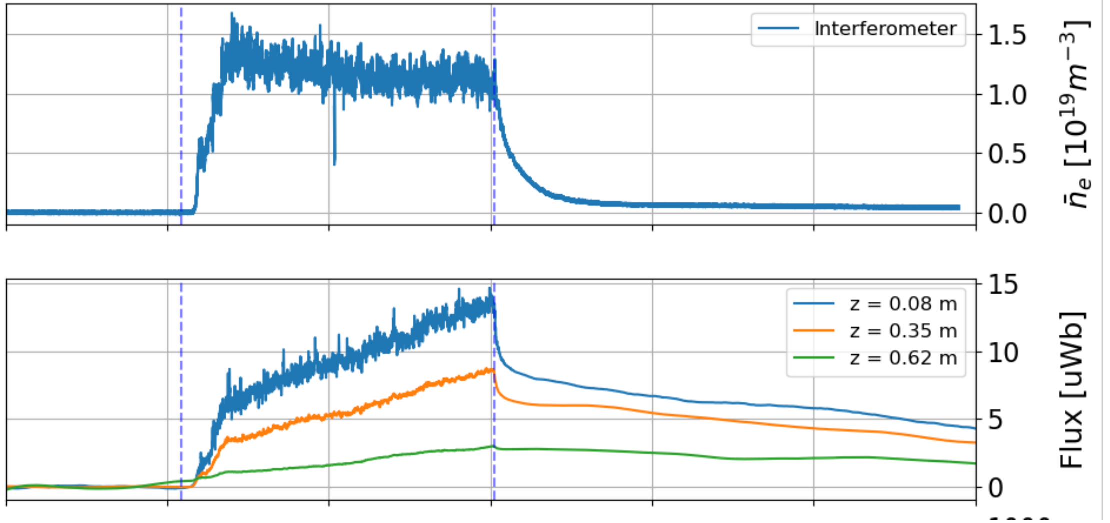
Plasma Heating Slide Raw Fluxes



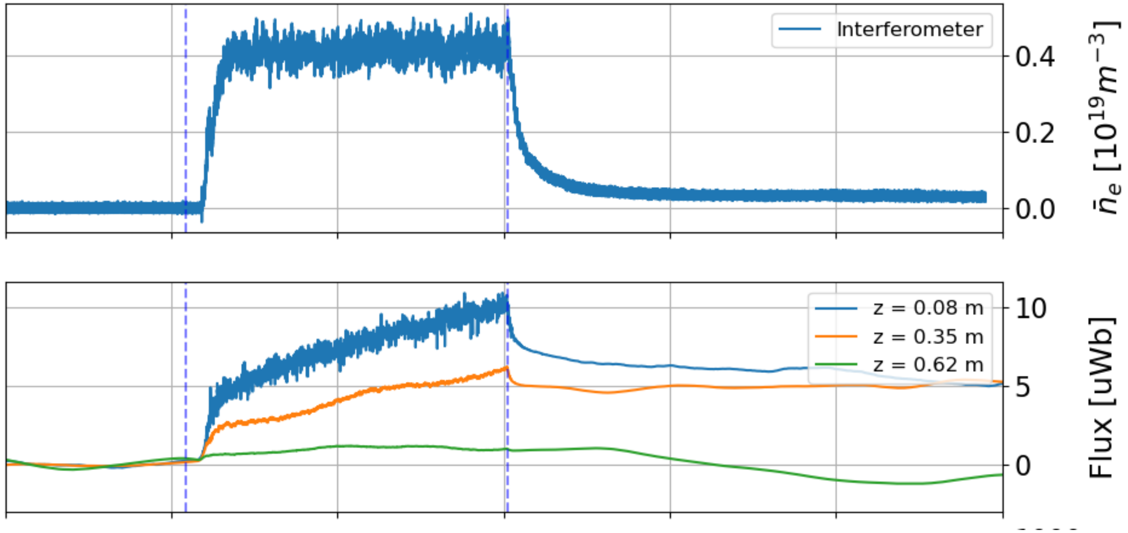
300kW High gas



300kW Low gas

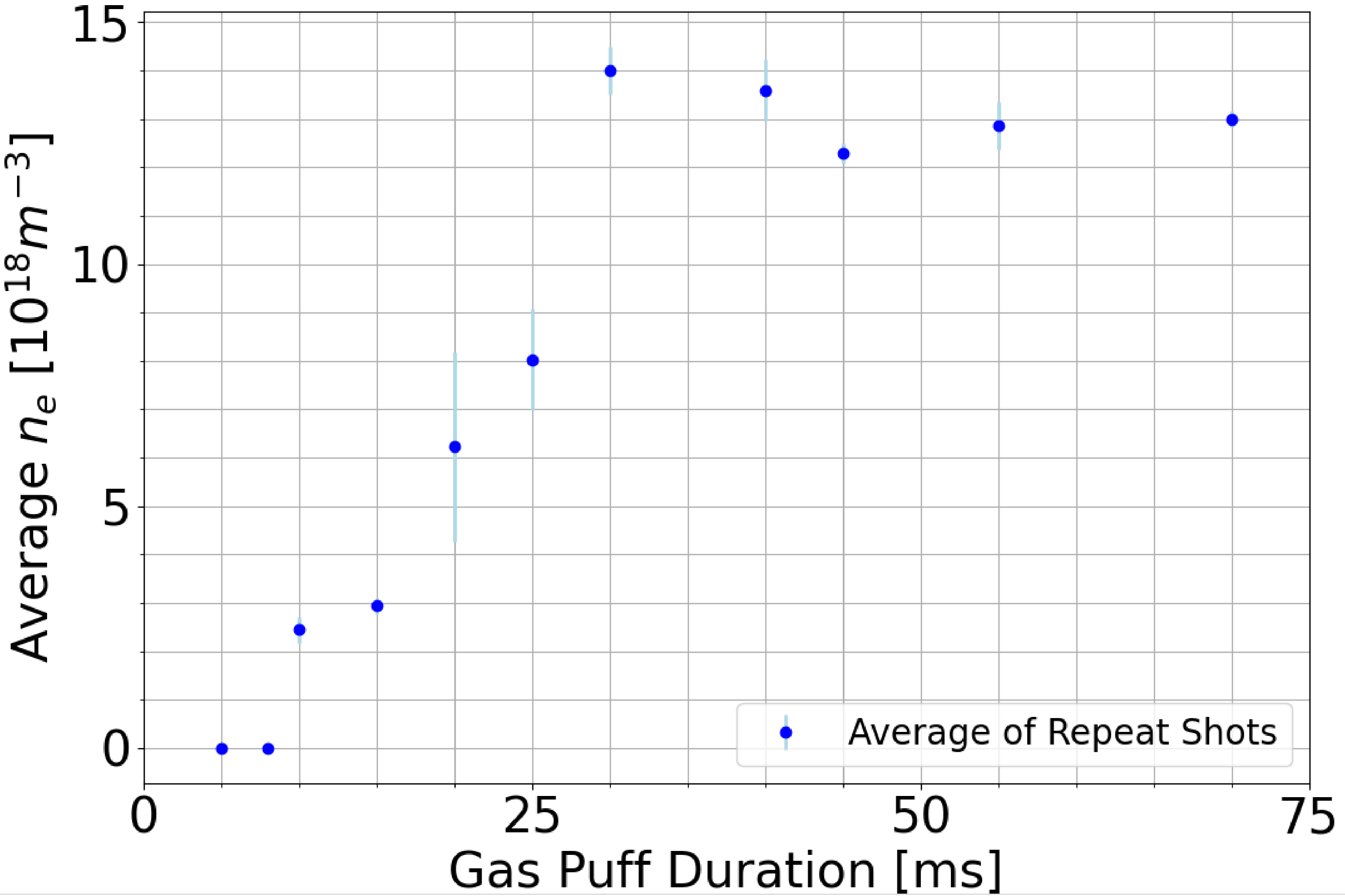


100kW High gas



100kW Low gas

X2 Gas Puff Scan



X2 Polarization Scan